A probabilistic comparison of times to flashover in a compartment with wooden and non-combustible linings considering variable fuel loads

by

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Abstract

Prescriptive fire safety codes regulate the use of combustible room linings to reduce fire risk. These regulations are based on classification systems which designate materials according to their relative hazard when exposed to a standard fire scenario. However, no quantitative data sets on the fire risk of wooden lining materials exist which take into account relevant uncertainties, such as movable fuel loads in compartments.

This work is a comparative risk analysis on the influence of wooden linings on the time to flashover in a compartment, considering uncertainties in the fuel load configuration. A risk model is set up for this purpose using B-RISK, a probabilistic fire design and research tool currently under development at BRANZ (Building Research Association of New Zealand) and the University of Canterbury. The risk model calculates fire spread in a compartment between fuel load items and from fuel load items to combustible linings. Multiple iterations are performed considering varying fuel load arrangements and input values sampled from distributions (Monte-Carlo simulation).

The functionality and applicability of the risk model is demonstrated, comparing the model with experiments from the literature. The model assumptions are described in detail. Some of the model inputs are defined as distributions in order to account for uncertainty. Parametric studies are conducted in order to analyse the sensitivity of the results to input parameters which cannot be described as distributions.

Probabilistic times to flashover are presented and discussed for an ISO 9705 compartment considering varying movable fuel loads and different lining configurations. The fuel load is typical for a hotel room occupancy. Effects of suppression measures are not considered. It is shown that flashover occurs approximately 60 seconds earlier if walls and ceiling are lined with wooden materials than if all linings are non-combustible. This value refers to the 5th percentiles of the time to flashover, i.e. in 5% of the cases flashover has occurred and in 95% of the cases flashover has not (yet) occurred. Referring to 50th percentiles (median values), the difference is approximately 180 seconds.

Furthermore it is shown that with wooden wall and ceiling linings in approximately 95% of the iterations flashover occurs, whereas with non-combustible linings 86% of the iterations lead to flashover. After 900 seconds, in 90% of the iterations flashover occurs if walls and ceiling are lined with wooden materials, and in 77% of the iterations if the linings are non-combustible. Using different wooden lining materials (non-fire retardant plywood, fire retardant plywood, and MDF) has no significant effect on the probabilistic times to flashover. Varying the fuel load energy density has an influence only when all linings are non-combustible and when the fuel load energy density is relatively low (100–200 MJ/m^2).

This work contains recommendations regarding the further development of B-RISK, the research into the fire risk connected with wooden room linings, and suggestions regarding the further development of prescriptive fire safety codes.

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Abbreviations

AS	Australian Standard
ASET	Available safe egress time
BRANZ	Building Research Association of New Zealand
BRE	Burning rate enhancement
CFD	Computational fluid dynamics
CO	Carbon monoxide
DFG	Design Fire Generator
DIN	German Standard (German Institute for Standardization)
EN	European Standard
FDS	Fire Dynamics Simulator
FLED	Fuel load energy density (unit: MJ/m^2)
FR	Fire retardant
FTP	Flux time product (unit: $s(kW/m^2)^n$)
HRR	Heat release rate (unit: kW)
ISO	International Standards Organization
MDF	Medium density fibre board (wood derivative)
OSB	Oriented strand board (wood derivative)
PE	Polyethylene
PP	Polypropylene
PU	Polyurethane
PVC	Polyvinyl chloride
RLF	Radiant loss fraction
RSET	Required safe egress time
SDI	Smoke Developed Index
SFI	Spread of Flame Index
SFPE	Society of Fire Protection Engineers

Terminology

Fire Spread	Spread of fire between items
Flame spread	Spread of flame on a lining or a fuel item after it has ignited
Fuel item	A piece of movable fuel load (such as furniture)
Fuel load	Amount of combustible material which can contribute to fire growth and severity
Fuel load configuration	Amount, type and spatial arrangement of movable fuel items
Hazard	Any situation, condition or configuration with the potential to create fire related harm (adapted from Hall and Watts [73])
Iteration	Deterministic calculation run with B-RISK considering input values sampled from probability distributions
Lining	A surface of a wall or a ceiling within a building which is exposed to a room
Lining material	A material which has the function of a lining. Lining materials can be solely fixed to a structure for aesthetical reasons or they can be part of a structural element which is either load-bearing or non-load-bearing.
Risk	Effect of uncertainty on objectives (ISO 31000 [29])
Simulation	Probabilistic analysis with B-RISK consisting of multiple iterations
Wooden lining	Lining out of wood or wood derivatives, such as OSB, MDF, or multi-layer solid wood panel

1 Introduction

1.1 Overview

The overall intention of this work is to contribute to the understanding of the fire risk associated with wooden lining materials. Fire risk is a wide ranging and complex topic – the influencing parameters and uncertainties range from the ignition of an item through to flame and fire spread and to the response of humans and structures in a fire. Therefore, and in order to provide accurate and sound information within the given project time frame, the scope of this work has to be confined. This project deals with the fire risk associated with lining materials during the fire growth phase, represented by the flashover time in the room of the fire origin.

This chapter gives basic information on relevant topics: wood and the fire hazards connected with it, code and testing requirements, modelling methods for flame spread on linings, fire risk. Before the research objectives are defined, the research of others is reviewed. In Chapter 2, the applied methodology is explained. The subsequent chapters follow the tasks outlined in Section 2.6.

A crucial tool for conducting the work described in this report is B-RISK. B-RISK is a probabilistic fire design and analysis software which is currently under development (more detailed descriptions of B-RISK are given in Sections 1.9 and 3.1). Another aim of this work is to contribute to the development of B-RISK by giving feedback on its functionality and to suggest improvements. This was done continuously during the entire project and adaptations were made in the software code several times. Therefore, different development versions of B-RISK were used in different stages and chapters of this work. It is stated, where relevant, which version was used for a certain task. The version history of B-RISK for the period relevant to this work can be found in Annex A1.

Regulatory structures for fire safety are different around the world. Due to the author's background, Swiss requirements are quoted in this work alongside the New Zealand requirements, where reference is made to building codes and regulatory requirements.

1.2 Wood as a building material

Wood has been used as a construction material since the beginning of civilization for both structural and decorative purposes. In modern times, its use as a structural material was restricted by building and fire safety codes to low-rise buildings up to two stories up to 1990 all over Europe (Östman [1]). In recent years, however, wood has been becoming more important as a building material. Its CO_2 storage capability is a key factor for meeting the challenges of climate change. It has significant advantages regarding energy efficiency due to its thermal characteristics and local availability; its favourable strength/weight ratio is appreciated when extending existing buildings. Often it is also the preferred material due to its visual appearance or when comfort criteria or cultural aspects should be considered. The use of wood is increasingly promoted and required by legal bodies in order to meet international environment agreements and support local industries.

Advances in engineering, manufacturing and assembly of timber structures have allowed multi-storey timber constructions to become increasingly competitive to other materials and to extend market shares significantly. Building codes in Europe have followed this development; it is the vision of European wood promoters and it is generally expected that in the near future restrictions for building with wood will be widely eliminated (Östman [1]).

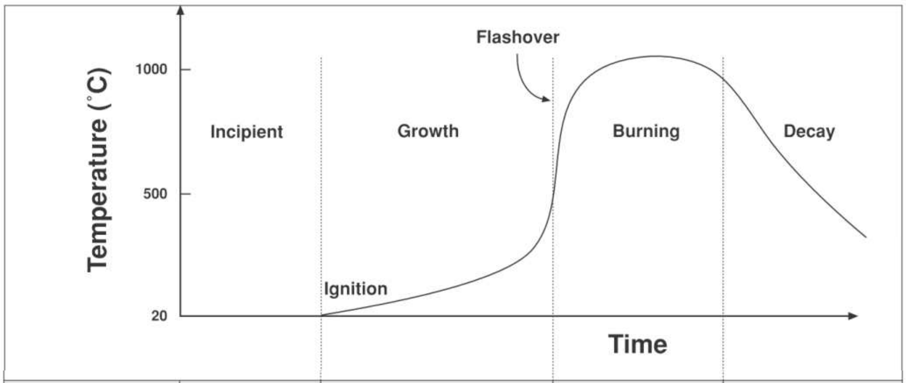
Many different systems exist for timber construction, of which Kolb [2] gives a comprehensive overview. Structural timber systems can consist of linear (e.g. columns or beams) or two-dimensional elements (such as floor or wall panels made out of solid timber, wood derivatives, or multiple layer compositions). Structural elements can be visible after completion or they can be covered by lining materials such as gypsum plasterboard or wood derivatives, depending on the architectural concept. Also wooden linings can be applied if the structural elements are non-combustible (e.g. internal or external wooden linings on concrete/masonry sub-structures).

1.3 Wood and fire hazard

In contrast to other common building materials such as masonry, concrete, or steel, wood is a combustible material and therefore poses specific fire hazards. Figure 1-1 shows a typical compartment fire development curve and defines the stages and their characteristics. This section briefly discusses what influence wooden linings can have on the development of a fire in a compartment.

In the incipient and growth stages, an item burning in the room can ignite wooden linings if it releases sufficient energy and if it is close enough to the lining. If ignition of the lining has happened, flames can propagate on the lining depending on several influence factors (to be described in more detail in Section 1.6). If flames propagate, linings can contribute to the production of heat, smoke and toxic gases and therefore to untenable conditions for occupants and to the onset of flashover.

After flashover, all combustible surfaces in a room are involved in the fire, i.e. they produce combustible gases. Consider two identical compartments A and B with identical movable fuel loads, but different linings: Compartment A with non-combustible (inert) linings and compartment B with combustible linings. If fully involved, compartment B would produce more combustible gases, i.e. the burning rate would be higher than in compartment A, due to the additional combustible surface of the linings. More gases would burn outside compartment B and therefore longer flames out of openings would be expected. This can be a hazard regarding the fire spread between rooms or storeys, and smoke migration to adjacent compartments. However, temperatures can be expected to be slightly lower in compartment B, because more energy is required for the gasification of the additional combustible surfaces and for heating up the gases, and less burning takes place inside the compartment due to reduced availability of oxygen inside the compartment. Both effects – longer flames out of openings and slightly lower temperatures inside compartments with wooden linings – have been observed in experiments (Frangi and Fontana [4], Hakkarainen [5]).



Stage	Incipient	Growth	Burning	Decay
Fire behaviour	Heating of fuel	Fuel-controlled burning	Ventilation-controlled	Fuel-controlled burning
Human behaviour	Prevent fire	Extinguish by hand (extinguiser, hosereel), escape	Death	
Detection	Smoke detectors Gas detectors	Smoke detectors Heat detectors Manual callpoints	External smoke and flame	
Active control	—	Extinguish by sprinklers or fire service. Smoke control	Control by fire service	
Passive control	Control of materials	Flammability, surface spread of flame	Fire resistance, containment, prevent collapse	

Figure 1-1 Typical compartment fire development curve with definition of stages and key terms (taken from Spearpoint [3])

Exposed wooden surfaces on structural members also add to the fuel load on top of the fuel load represented by the movable items. Depending on the configuration, this can lead to longer burning and decay periods as well as more intense burning out of vents as described above.

Although highly relevant in terms of the overall fire risk connected with wooden linings, the post-flashover stages are not treated in this study for the reason discussed in Section 1.1.

1.4 Performance requirements for linings

Regulatory frameworks for building construction are different around the world. However, in terms of fire safety, the *objectives* are similar as summarized by Buchanan [6]: to protect life and property from the effects of fire (compare also the New Zealand Building Code fire safety clauses [7] and the Swiss fire safety codes [8]). Referring to Figure 1-1, the importance of the fire safety objectives in the different fire development stages can be qualitatively described as shown in Table 1-1. In fire safety design, the pre-flashover stages are important when looking at life safety of occupants in the room of fire origin and adjacent or connected rooms. The post-flashover stages are important when looking at property protection objectives, but also for life safety of occupants located in the same or in adjacent buildings.

In order to achieve the required level of safety regarding the objectives, building codes specify *functional requirements* and requirements regarding *performance* (using the same terms as the New Zealand Building Code [7]). Regarding linings, the requirements for passive control measures are of interest. These distinguish between requirements concerning the generation of toxic gases, smoke and heat (*reaction to fire*) of single materials on the one hand and requirements concerning the *fire resistance* of building elements or assemblies on the other hand (this again is similar in different countries, e.g. Switzerland [8]). Fire resistance issues will not be looked at in this work. However it shall be mentioned that wood has, in spite of its flammability, a predictable fire resistance behaviour. Methods are available for determining the fire resistance in terms of fire containment and structural stability; see Buchanan [6] for more information on this topic.

Table 1-1 Importance of fire safety objectives in fire development stages

	Life safety	Property protection
Pre-flashover stages	✓✓✓	✓
Post-flashover stages	✓✓	✓✓✓

✓✓✓ Very important
✓✓ important
✓ Less important

Up to now building codes do not specify objectives or required levels of safety quantitatively. In terms of reaction-to-fire requirements, the New Zealand Building Code [7] requires: “Interior surface finishes on walls, floors, ceilings and suspended building elements, shall resist the spread of fire and limit the generation of toxic gases, smoke and heat, to a degree appropriate to (a) the travel distance, (b) the number of occupants, (c) the fire hazard, and (d) the active fire safety systems installed in the building”. Again, the requirements in the Swiss fire safety codes [8] are similar, albeit slightly different in detail. Loosely translated they read: “Combustible materials may be used only if they do not inadmissibly increase the fire hazard. Important criteria are in particular (a) fire and smoke performance, flaming droplets/debris, heat release, development of toxic gases, (b) purpose and extent of application, (c) number of occupants, (d) number of storeys, (e) type of construction, location, dimension and occupancy of buildings … or fire compartments”.

Typically, legislators provide a set of detailed, prescriptive measures to be considered in the design and construction of a building – e.g. flammability and smoke production classes for linings in different applications (more detail is given in Section 1.5). It is then assumed that, if these measures are put in place, the objectives and performance requirements are reached (“deemed-to-satisfy” solutions). These measures may differ from country to country to a considerable extent.

Alternatively, building codes can allow for designs which deviate from the prescriptive set of measures, commonly called performance-based designs. These allow for innovation and more flexibility in architectural conception and material choice. The purpose of a performance based design is to prove that a specific design meets the objectives and requirements of the building code. However, this is not always straightforward, since the objectives or requirements, as mentioned previously, are not usually quantified. Therefore, performance-based designs typically require significant efforts and are costly regarding human and financial resources. Hence it follows that prescriptive “deemed-to-satisfy” sets of measures have strong relevance for the overall construction activity of a country, and will maintain this relevance for some time.

1.5 Prescriptive requirements and testing of lining materials

In the following, the prescriptive requirements for lining materials in Switzerland and New Zealand are outlined for illustration, and information on relevant testing methods is given.

In Switzerland, wall and ceiling lining materials are tested vertically at bench scale according to a specific national standard [10]. The samples are ignited with a 20 mm propane flame. The flame height resulting from burning of the sample and the optical density of the smoke are measured. Other procedures apply for floor coverings, textiles and loose materials. Non-combustible materials are tested according to DIN 4102 Part 1 [11]. Materials are classified according to their flammability and smoke production. The relevant section of the fire safety codes [12] then specifies minimum requirements in terms of flammability and smoke production classes for different applications (linings, insulations, installations, etc.). It is intended that the Euroclasses (EN testing and classification methods) will be introduced on the occasion of the next revision of the fire safety codes [13]. Requirements have been adjusted over time, considering developments in building industries and including experiences and lessons learnt from significant fire incidents.

In Switzerland, wooden wall and floor linings can be applied in non-high-rise buildings without restrictions, except in exitways. Exitway linings must be non-combustible. In high-rise buildings (more than 8 stories or highest floor more than 22 m above ground level), wooden linings are “acceptable in single rooms” (but not in exitways) [12].

As summarized by Wade [14], the relevant testing standard for lining materials in New Zealand is AS 1530 Part 3. Small scale vertical samples are exposed to a radiant panel and materials are classified regarding four performance criteria (“Early Hazard Indices”). The New Zealand Acceptable Solution C/AS1 [7] specifies requirements regarding two of these criteria for compliance with the building code – the Spread of Flame Index (SFI) and the Smoke Developed Index (SDI). New Zealand is the only country in the world using AS 1530 and might, according to Collier et al. [15], introduce an international standard for regulating the fire properties of linings in the future.

In New Zealand, SFI and SDI restrictions apply which require wooden wall and ceiling linings in assembly occupancies to be fire retardant treated. However if such a building is sprinklered, wooden wall linings are acceptable without fire retardant treatments. In other occupancies, wooden wall and ceiling linings are generally acceptable, except in exitways. Linear structural timber elements are exempted from SFI and SDI restrictions, also in exitways [7].

There are many other test methods for determining the fire hazard of lining materials at bench and large scales. The most relevant methods are summarized and discussed by Madrzykowski and Stroup [16]. An example for the bench scale test method is the cone calorimeter test, which allows determining ignition and heat release properties of a material exposed to an external heat flux (see Babrauskas [17] for an introduction). Full scale tests typically examine flame spread properties of lining materials exposed to a certain fire scenario, e.g. a gas corner burner in the ISO 9705 room-corner test [18]. This test consists of a compartment 3.6 m × 2.4 m × 2.4 m with a 0.8 m × 2.0 m opening (Figure 1-2). The test material is fixed to the interior walls and/or ceiling and exposed to a gas burner fire in the corner. The burner has a square burning area 0.17 m wide and an output of 100 kW for 10 minutes followed by 300 kW for another 10 minutes. The main measurement parameter is the rate of heat released by the burner and the linings. This configuration is the reference scenario for the evaluation of surface lining flammability hazard in Europe (Hirschler [19]); the basic classification criteria are the contribution to fire growth and the time to flashover.

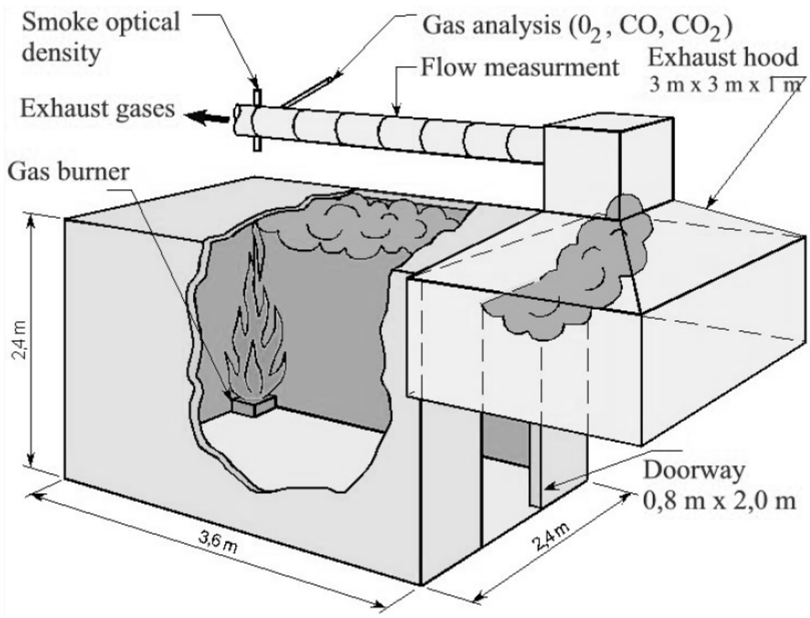


Figure 1-2 Schematic layout of the ISO 9705 room-corner test (taken from Collier et al. [15])

1.6 Methods for predicting flame spread on linings

Flame spread over surfaces of solids (and therefore linings) is a phenomenon consisting of complex processes. The main factors influencing flame spread on linings are (adapted from Drysdale [20], Table 7.1):

- lining configuration:
  - chemical composition and thermal properties of the lining material.
  - thickness and surface geometry of the lining material.
  - orientation of the surface, direction of flame propagation.
- environmental conditions:
  - initial temperature of the surface, imposed heat fluxes (e.g. from burning items or upper layer).
  - air velocity in the vicinity of the surface (e.g. due to vent flows or flows in vertical shafts).

Drysdale [20] also gives an overview on what attempts have been undertaken by different researchers to model flame spread on surfaces. Hasemi [21] describes the fundamental physics of surface flame spread in detail. He distinguishes between wind-aided flame spread (which applies for upward wall flame spread and flame spread beneath ceilings) and opposed-flow flame spread (applies for horizontal or downward flame spread on walls). Hasemi points out that his correlations are for the understanding of the basic flame spread principles only, and that e.g. flame spread on linings in buildings depends on additional factors. The modelling of flame spread on linings in buildings is described in more detail in the following.

For some time, attempts to model flame spread on linings focussed on predicting heat release rates and flashover times from linings in the ISO 9705 room-corner test using material properties obtained from cone calorimeter tests. One of these models is Quintiere's room-corner model [22]. It has been shown by Quintiere [22] and Wade [23], that this model is able to predict the heat release from linings in the ISO 9705 room-corner test with reasonable accuracy for a range of materials. However it should be mentioned that the applicability of this model has not been proved for other materials or other room sizes. Rather Wade [23] has shown that predictions for larger rooms are less accurate. Researchers and designers should bear this in mind when applying Quintiere's room-corner model.

Quintiere's room-corner model has been adapted into the computer zone model BRANZFIRE [24]. Besides BRANZFIRE, also the CFAST computer zone model includes a lining flame spread model (Lattimer et al. [25]). Walton et al. [26] present a selection of the many available computer zone models, however apart from BRANZFIRE and CFAST none are reported to include lining flame spread models.

There have also been attempts to model flame spread on linings with CFD simulations such as FDS (Yan and Holmstedt [27], Moghaddam et al. [28]). However the results are inconsistent and more research is needed in order to be able to predict flame spread on linings reliably.

It can be concluded that a series of models is available for predicting the heat release rate from linings for certain materials and configurations, but there is no generally applicable model available with which engineering calculations could readily be performed.

1.7 Fire risk associated with wooden lining materials

Before discussing the risk which is connected with the fire hazard of wooden linings, the overall scope of this research is repeated: it concentrates on the pre-flashover fire stage and the room of fire origin. Speaking in terms of risk management conventions such as ISO 31000 [29], the objective would be a certain level of health of room occupants in the case a fire starting in that room. The lining materials would be a risk source (or a hazard if following the terms defined at the beginning of this document).

ISO 31000 [29] specifies that uncertainties should be explicitly addressed in risk management. Table 1-2 shows uncertainties in connection with the flame spread on linings, along a timeline which is confined to the scope defined above – from fire ignition to the response of occupants in the room of fire origin. The list in Table 1-2 could be extended beyond the room of fire origin, if the intention was to investigate the risk in a wider context, e.g. considering exitways. However this is not part of this study.

Table 1-2 Uncertainties influencing the risk associated with linings during fire growth stage

Timeline		
	1.	Probability of ignition – does **ignition of an item** take place?
	2.	Does the first ignited item release enough energy and is it located closely enough to the lining, so it can **ignite the lining?** Alternatively, can it ignite other items which can then ignite the lining?
	3.	If linings are ignited – are the lining configuration and the environmental conditions in such a way that **flames can propagate on the lining?** How fast do they propagate?
	4.	Are **other items involved** in fire spread (ignited by the first ignited item or the lining) and contribute to the fire growth in the room? How many of them are present, and what is their spatial arrangement? What are their ignition and burning characteristics?
	5.	Are **occupants present** in the room of interest? What is their state of alertness and ability to escape?
	6.	Are **detection or suppression systems** present which can influence events 2. to 5.?

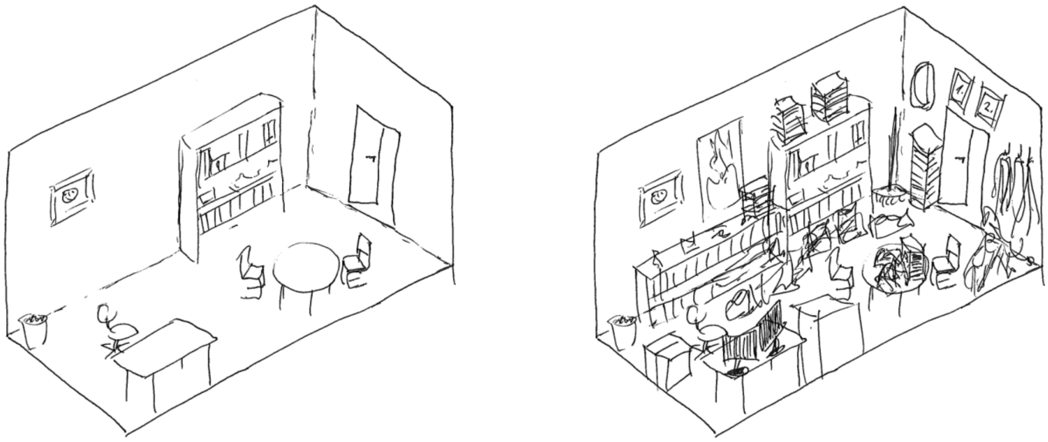
When considering Table 1-2, it becomes clear that the findings from a reference scenario such as the ISO 9705 room-corner test provide answers to only a small fraction of the uncertainties which are relevant to the objective (in this case the level of health of the occupants in the room). Therefore, a lot of uncertainties would still have to be addressed if the risk to these occupants is to be treated. Strictly speaking, any set of prescriptive fire safety requirements is such a risk treatment in a lumped form – and therefore intrinsically addresses the uncertainties. However, the only features which are specifically controlled (and therefore explicitly addressed) by the prescriptive requirements are the burning characteristics of the lining material. All other uncertainties are intrinsically addressed by the reference scenario as a "reasonable worst case scenario". It shall not be argued here whether "intrinsically" is equal to "not explicitly" – but at least it can be stated that it implies "not of a quantitative nature".

Furthermore, the sets of prescriptive requirements as lumped risk treatments are adjusted to an accepted level of risk, which is typically not quantified. This lack of quantified risk criteria and data makes it difficult to answer questions on whether certain materials indeed present a risk to an extent that their application has to be restricted – and such questions are unavoidable as long as restrictions are in place (as an example, refer to a workshop on fire safety in multi-storey timber buildings at the University of Canterbury [30]). There may also be the opposite case: a supplier of building materials launches a new lining material with better flame spread properties than current regulations require (e.g. a fire retardant wood derivative). For promotion purposes they might present the accepted hazard of common wooden linings in an exaggerated way (see the press report [31] and a promotion video [32] for a product launch of a European OSB manufacturer as an example). Attempts like this can lead to confusion among building owners, designers, contractors, and authorities.

In other words, a reference scenario is arguable as long as there are no quantitative conventions to base it on – e.g. the question might be raised whether a relatively weak burner in the corner of a room representing a waste bin is in fact a better reference scenario than, say, a stronger burner in the centre of a room or against a wall representing a sofa.

The lack of quantified risk criteria and data on relevant uncertainties also is an issue when carrying out performance-based design. As mentioned in this section, the accepted level of risk is not stated in terms of health of occupants (which is the objective regarding the performance of linings in our context), and no quantitative data is readily available for most of the uncertainties shown in Table 1-2.

As a conclusion it can be stated that the fire risk associated with lining materials not only depends on the lining itself, but also on a number of other parameters, which contain uncertainty. Therefore, the fire risk associated with lining materials has a probabilistic nature. Consider Figure 1-3 as an illustration of the uncertainty in terms of other items involved in fire spread (points 2 and 4 in Table 1-2). Assuming that the room geometry and the lining material are exactly identical in both office rooms 1 and 2 – the effect of the lining material as a risk source on the life safety objective is not the same in the two rooms.



Office room 1 Office room 2

Figure 1-3 Two office rooms, illustrating different fire risk at identical room geometries and lining materials

1.8 Existing research on fire hazard and fire risk associated with lining materials

Important research into the modelling of lining flame fire spread has been mentioned in Section 1.6. More current research, e.g. by Shields et al. [33] or Zhan and Yang [34], still focuses on testing and measuring lining flame spread and its effects on room conditions for specified scenarios. There are also attempts to develop new models for predicting flame spread on linings (Weng et al. [35], Hansen and Hovde [36]).

Almost no research has been carried out in assessing the risk associated with lining materials as described in Section 1.7. Björkmann and Mikkola [37] carried out a risk assessment of a 4-storey residential building with specialized software, comparing the risk of death in a timber frame and a concrete building. Flame spread on linings, however, was not included. The only difference between the concrete and the timber building were the thermal properties of the compartment boundaries. Consequently there was no evident difference in the calculated values of risk of death between the timber and the concrete building. More recently, Cheng and Hadjisophocleous [38] have modelled fire spread in a building incorporating uncertainties. Also in this research flame spread on linings was not explicitly considered – the fire growth stages were modelled using a t-squared fire growth.

Lai et al. [39] conducted four experiments of room fires with varying fuel load and lining configurations in order to investigate the influence of the ignition source location on fire spread. The room was 6 m × 5 m × 3.3 m and the walls were partly lined with wooden material. It was found that the HRR development over time is different for different arrangements. Furthermore, Lai et al. [39] present an interesting overview on tests carried out by other researchers with furnished ISO 9705 compartments. Different lining materials were included. It is noticeable that flashover occurred generally between 100 s and 178 s. The shortest flashover time was recorded in an experiment where the walls and ceiling were lined with paper-faced gypsum wallboard. Slightly longer flashover times were observed for plywood walls and the longest flashover time was in a compartment with concrete walls. How the furniture and the linings contributed to fire growth was not presented.

In conclusion, there are a few research reports available which compare flashover times and heat release rates of furnished rooms at specific scenarios (furnishings, linings). However they are still scenario-based. Generic, quantitative figures on the fire risk associated with lining materials have not been published so far.

1.9 B-RISK: a probabilistic fire design and analysis tool

In a joint project, BRANZ and the University of Canterbury are developing a probabilistic tool for fire research and engineering, which is in the following called B-RISK. B-RISK is an extension to the existing, deterministic computer zone model BRANZFIRE. The main novelties in B-RISK are:

- An item-to-item fire spread sub model, which allows the user to model realistic fire growth patterns based on ignition and burning characteristics of single items.
- The possibility to assign probability distributions to the input parameters for the zone model, the detection devices, and the fuel items.
- The Design Fire Generator (DFG) – a module that populates a space with user-defined fuel items. The user has the choice to place the items manually at specific spatial locations, or to let the DFG randomly populate the room. In the case of the random population, a target FLED or a FLED distribution can be specified (FLED = fuel load energy density – see Section 4.5 for more information).

With these tools, the uncertainties in model assumptions, especially in the fuel load configuration, can be considered for quantitative risk analysis.

The overall objective for the development of B-RISK is according to Baker and Wade [40] "to improve the quality and methodology currently employed by fire safety engineering practitioners … and to support effective performance-based fire safety design …". Baker and Wade's paper also gives an overview on the research project hereto. A more detailed description of the functionality of B-RISK is given in Section 3.1.

1.10 Research objectives

From the previous sections it is concluded that

- Fire growth on wooden linings can be a hazard regarding fire safety objectives.
- Prescriptive requirements for lining materials are based on classification systems which designate materials according to their relative hazard when exposed to a standard fire scenario.
- Methods for predicting the fire growth on linings are available for certain configurations, but not for general applicability.
- No quantitative data sets exist on the fire risk of wooden lining materials which consider all relevant uncertainties.
- The probabilistic fire design and research tool B-RISK is in development, which allows the consideration of uncertainties for quantitative risk analyses.

As mentioned in Section 1.1, the overall intention of this work is to contribute to the understanding of the fire risk associated with wooden lining materials. Considering the conclusions above, the following objectives are stated for this work:

1. To conduct a quantitative, comparative analysis of the fire risk associated with wooden lining materials using B-RISK.
2. To comment on the functionality of B-RISK for this purpose and give suggestions for improvement to the developers of B-RISK.

In the next chapter, the merits of a comparative risk analysis are shown and the necessary risk parameters defined. The scope of the work is defined and the necessary tasks are outlined.

2 Methodology

2.1 Absolute vs. comparative risk analysis

Fire risk analysis can be done in an absolute or in a comparative way. Both methods can be applied for quantitative risk assessment and therefore provide numerical values for the risk being evaluated. An absolute risk analysis, however, provides values which are "correct" in their magnitude as best as possible, whereas a comparative risk analysis provides figures on the difference in the risk between two or more scenarios. The absolute magnitude of the values is therefore not of primary interest in a comparative risk analysis, but the difference between them. Comparative risk analyses make use of the fact that assumptions which might be difficult to justify, influence all scenarios equally. While this does not mean that changes in the assumptions would not cause differences in the results, their influence can be analysed by means of sensitivity analyses and be considered in the risk evaluation. Absolute risk analysis is more challenging in this regard, because all input values and assumptions would have to be "correct" in their magnitude.

A comparative approach is chosen for this study, since the interest is rather in how much wooden linings add to the fire risk compared to non-combustible linings than in the absolute values. This choice is supported by Hall Jr. [41] who, regarding the fire risk of products, suggests that "… fire risk analysis should proceed through calculations of differences, that is, fire risk with the product of interest versus fire risk with something else substituted for the product of interest". It "should usually be avoided to … try to measure loss in terms of the product's share of responsibility for overall fire severity", because "such measures tend to be far too subjective and require answers to inherently unanswerable questions".

The next two sections establish the risk criteria necessary for the comparative risk analysis.

2.2 Timeline as an appropriate reference parameter

As defined in Section 1.10, the primary objective of this work is to conduct a quantitative analysis of the fire risk associated with wooden linings. It has been mentioned before that this work is confined to an analysis of the fire growth phase (on a time scale) and the room of fire origin (on a spatial scale).

Different risk criteria could be applied for an analysis of the fire risk associated with wooden linings. The *time* until untenable conditions for occupants occur in the room of fire origin is a useful criterion when designing for life safety objectives (ASET/RSET calculations). Life safety objectives, in their turn, are primarily to be addressed in the fire growth phase (compare Table 1-1). Untenable conditions for occupants could be e.g.

- a certain HRR.
- a certain height of the upper layer interface.
- a certain visibility at a certain room height.
- a certain level of toxic gas concentrations at a certain room height or a summed dose of such gases.

- a certain temperature at a specified room height, or a summed dose of thermal exposure.

On the other hand, if looking at property protection objectives, a criterion such as the extent of damage (area or volume affected by fire) would be more suitable. However, this criterion would also have to be put into relationship with the *timeline* of a fire in order to be able to consider e.g. detection, fire spread, suppression or burnout. Therefore, the timeline would be an appropriate reference parameter for most risk analyses regarding fire and it is particularly so for the present study.

2.3 Flashover as an appropriate criterion

In the previous section, a list of criteria for judging the tenability for occupants was given. The list starts with the HRR, one of the major assumptions when modelling fires with tools such as BRANZFIRE or B-RISK. It is noticeable, however, that all of the subsequently listed criteria are governed by the HRR – a higher HRR will faster lead to untenable conditions than a lower HRR. It is one of the reasons why the HRR is also referred to as the "single most important variable in fire hazard" (Babrauskas and Peacock [42]). With reason it can be said, therefore, that the HRR is a sensible representative of all the criteria listed.

The HRR is also decisive in determining whether flashover in a room will occur or not. Flashover is of crucial importance for fire safety. Drysdale [20] mentions along with other authors that "anyone who has not escaped from a compartment before flashover is unlikely to survive". Post-flashover fires impose a far larger hazard in terms of fire spread to other parts of the building or to other buildings and to occupants in, or evacuating from, other rooms of the same building than pre-flashover fires. Furthermore, post-flashover fires represent different and more challenging situations for fire-fighting compared to pre-flashover fires. The significance of the time to flashover is acknowledged in the EN where it constitutes a criterion for the classification of lining materials regarding flammability hazard (as mentioned in Section 1.5).

In conclusion, flashover is a crucial criterion in fire safety. It represents the effect of the HRR as the "single most important variable in fire hazard" on life safety and property protection objectives. Therefore, the flashover criterion is an appropriate criterion for the present risk analysis. By defining time to flashover as a decisive criterion, further discussion on what specific tenability values (e.g. gas concentration) and on what height they should be applied can be avoided. The time to flashover is almost completely dependent on the HRR development in the room, rather than on inputs requiring more investigation and assumptions (such as species yields of the burning items). Defining time to flashover as a decisive criterion therefore contributes to a "consistent level of crudeness" in input assumptions and output accuracy (phrase coined by Elms, cited by Platt et al. [43]).

Nevertheless "flashover" needs more specification in order to consider it as a risk criterion in a fire model. This is because it is "the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure" (ISO definition given by Karlsson and Quintiere [44]) rather than a defined point in time of fire development. Often in tests flashover is determined by observing the ignition of an indicator item at floor level (Shields et al [33] e.g. use crumpled newspaper). In other tests (Maag and Fontana [45] or Lai et al. [39]) flashover is defined when flames emerge out of the window. Other commonly used criteria to describe flashover are:

- critical HRR values (correlations such as Thomas', given by Buchanan [6], or Babrauskas' [46]).
- 20 kW/m^2 irradiance at floor level (Waterman's criterion, described by Drysdale [20]).
- Average upper layer temperature 500–600 °C (Karlsson and Quintiere [44]).

These criteria would all be easily quantifiable and computable and could be used for a quantitative risk analysis. For the present study, the computer model B-RISK is applied (to be described in more detail in Section 3.1). Current versions of B-RISK are programmed in such a way that B-RISK can stop iterations at flashover, assuming flashover to occur either when irradiation at floor level exceeds 20 kW/m^2 or the upper layer temperature exceeds 500 °C. It is therefore obvious to use one of these criteria. Out of them, Waterman's criterion (20 kW/m^2 irradiation at floor level) describes the actual physical effect (involvement of all combustible surfaces) better when the judgement should be independent from room height and ventilation openings. On the other hand, the 500-°C-criterion requires less calculations and inputs and is therefore more robust against model and input uncertainties. A comparison of flashover times applying both criteria has shown inconsistencies when using Waterman's criterion (Section 5.3). Therefore the 500-°C-criterion is used in this study.

It should be mentioned here that the actual values for all of these criteria are not fixed at all, as discussed by Peacock et al. [47] or more recently Babrauskas and Jones [48]. Also, applying different criteria would result in different flashover times. Since this study is a comparative risk analysis, the values are not discussed and justified in more detail.

2.4 Confining timeline and physical boundaries

A complete assessment of the risk associated with wooden linings in the room of fire origin would have to include the complete timeline as shown in Table 1-2 – from the ignition probability through to occupants' responses and detection and suppression. This study, however, is confined to an analysis of steps 2 through to 4, as far as they occur before flashover. Uncertainties in the likelihood of fire occurrence, occupants' presence and response, presence and reliability of fire detection and suppression systems are not included in the study.

Since this work is confined to the room of fire origin, occurrence and intensity of vent fires and migration of heat, smoke and toxic gases to adjacent or connected compartments are also not included.

2.5 Other restrictions

Due to the complexity of the topic, some more restrictions have to be applied to the scope of the study. While it is the intention to investigate the fire risk associated with wooden linings compared to non-combustible linings, only three wooden lining materials are considered. Wood is an inhomogeneous material with widely differing properties for different species and derivatives. Three representative materials are chosen therefore and compared to a non-combustible lining.

Room geometry and ventilation openings are crucial for the fire development in a compartment. Different results would be expected for different configurations in this regard. This study focuses on the ISO 9705 compartment geometry (Section 1.5, Figure 1-2), because the applied method for predicting fire spread on linings is validated for this configuration (Quintiere's room corner model, Section 1.6), and many of the experiments which can be found in the literature and used for discussion and evaluation are typically conducted in ISO 9705 rooms.

Linings can theoretically be applied on walls, ceilings and floors. On any one of these, different materials could be applied within a room, and even a wall, a ceiling, or a floor could be lined with different materials partially. In this study the combinations as shown in Table 2-1 are considered, with the lining mentioned applied on the entire relevant compartment boundary.

Table 2-1 Lining combinations used in this study

	Linings		
	Walls	Ceiling	Floor
Case A	non-combustible	non-combustible	non-combustible
Case B	wooden	wooden	non-combustible
Case C	wooden	non-combustible	non-combustible
Case D	non-combustible	wooden	non-combustible

2.6 Tasks

In the following, the tasks necessary for the risk assessment are outlined and references to relevant chapters of this report are given:

1. Test whether B-RISK is capable for modelling the intended purpose, since the software is under development and verification and validation have not been documented so far. If necessary and feasible in the time given, adapt and debug functions which are necessary for the intended purpose in consultation with the B-RISK developers (documented in Chapter 3).
2. Model a documented experiment with B-RISK and compare the modelling results with the experiment results (documented in Section 3.3).
3. Define the input values for the simulations (documented in Chapter 4).
4. Show the functionality of the model by means of a study of selected parameters with deterministic runs (documented in Chapter 5).
5. Run final simulations with B-RISK; present and discuss the results (documented in Chapter 6).
6. Conduct sensitivity analyses for values which are not varied or cannot be varied (documented in Chapters 5 and 6);
7. Report recommendations to the developers of B-RISK and future researchers (documented in Chapter 8).

3 Capability of B-RISK

3.1 Model description

3.1.1 The parent model BRANZFIRE

BRANZFIRE was developed in the 1990s and "is intended for evaluating the performance and hazard associated with room fires including combustible room lining materials" (Wade [24]). It is a multi-room zone model applicable to room fire scenarios and includes several sub-models for modelling e.g. fire growth on linings, detection devices activation, vent glass breaking, and post-flashover conditions. The principal inputs required from the user are:

- room and vent geometries.
- thermal properties of the room boundaries.
- fire HRR and species yields.
- environment data.

Detailed technical reference and user guidance can be obtained from Wade [24] [49].

3.1.2 The BRANZFIRE fire growth sub-model

The BRANZFIRE fire growth sub-model calculates flame spread on linings and the resulting heat release from wall and ceiling lining materials. It is described in greater detail here because of its importance for this study.

The user is required to specify an initial fire source in terms of HRR, burner width, and burner location (room centre, against a wall, or in a corner). BRANZFIRE calculates the flame height and the heat flux from the fire to the wall and ceiling linings, which ignite when the Flux Time Product (FTP), a material-dependent value of incident heat flux integrated over time, is reached. The FTP for a lining material is calculated from cone calorimeter data, which can be taken from a materials database provided in BRANZFIRE or, alternatively, provided by the user. There is an alternative method for determining the ignition time via a critical surface temperature. However the FTP method is the preferred method and is used for this study.

Once a lining is ignited, the progression of the pyrolysis front in the vertical and horizontal directions is calculated according to Quintiere's room-corner model [22]. The flame spread velocities depend, among other factors, on the heat released by the ignition source. The HRR from the lining is calculated as a function of the pyrolysis area and the cone calorimeter HRR data of the lining material. Burning wall linings can also ignite ceiling linings.

Refer to the BRANZFIRE Technical reference [24] guide for a more detailed description of the fire growth sub-model including all relevant correlations.

3.1.3 B-RISK – transforming BRANZFIRE into a probabilistic tool

As already mentioned in Section 1.9, BRANZFIRE is currently being extended by additional sub-models in order to transform it into a probabilistic fire design and analysis tool, called B-RISK. Also the functionality is extended in a way that B-RISK can run multiple iterations per simulation, considering different values taken from probability distributions for input values (Monte-Carlo simulation). As an example, normal, triangular, or uniform distributions can be defined for the exterior and interior initial temperatures in order to consider uncertainty and historical data. B-RISK samples values from these distributions for every iteration, producing different outputs per iteration depending on the sampled values. A simulation output can then be expressed as a cumulative density function describing the outputs of the single iterations. This enables e.g. fire safety engineers to compare a simulation output against a probabilistic statement of building performance (Baker et al. [50], Baker [51]).

Two new sub-models allow for the accounting of uncertainty in the fuel load configuration and, ensuing from this, uncertainties in fire spread. These two sub-models are described in more detail in the following sections.

3.1.4 The radiative fire spread sub-model

In B-RISK, the user can specify one or several fuel items by defining the following characteristics for each item:

- geometrical outline (length, width, height) and elevation.
- mass and heat of combustion.
- HRR time history and radiant loss fraction.
- CO and soot yields.
- ignition characteristics derived from cone calorimeter data (FTP indices, FTP limits, and critical fluxes for piloted and radiant ignition).
- probability of being located against a wall.

Some of these input values can be defined as probability distributions for considering uncertainty and statistical data. More information on the derivation of these data is given in Section 4.4.

The user has the choice to place the fuel items manually at defined spatial locations in the compartment, or to let the DFG (see next section) randomly populate the room. Also the user can define an item to first ignite, or let B-RISK randomly choose an item to first ignite.

Based on the spatial arrangement and the ignition characteristics of the items, it is calculated whether and when secondary items ignite. Radiation from the first and other ignited items is considered when calculating the FTP for piloted ignition at secondary items. Radiation from the hot layer and the compartment boundaries is considered when calculating the FTP for auto ignition. Detailed information on the radiative calculation model can be obtained from Baker et al. [50] and on the FTP calculations from Baker et al. [52].

The HRR histories of all ignited items are cumulated, taking into consideration their ignition time, and used for the zone model calculations.

3.1.5 The Design Fire Generator (DFG) sub-model

As mentioned previously, the user is able to let the DFG randomly populate the room instead of placing items at specified locations. The DFG takes a random item from the items list and places it at a random position in the room. While doing so it considers the probability of the item to be located against a wall – if the probability is 1, the item will always be put against a wall, if the probability is 0, the item will never be put against a wall. A vent clearance distance can be defined in order to specify areas which are not expected to be furnished in the vicinity of vents. The DFG repeats the routine until

- no more items are available from the list.
- no more item from the list fits into the room.
- the specified target FLED or the sampled value from a FLED distribution is reached or exceeded by the actual FLED. The actual FLED is the FLED from the items already placed in the room calculated from the mass and the heat of combustion specified in the items list.

The user can specify items to be taken from the list only once or a certain number of times. The first item randomly taken from the list is also the item to first ignite, unless the user specifies a certain item to be first ignited. In the latter case, this item will be placed in the room first, before the other items are randomly placed as described above.

This procedure is repeated in every iteration. Due to the randomness in the placement order and the spatial arrangement of items, different fuel load configurations result for different iterations, and ensuing from this different HRR-time histories for the compartment (provided there are enough items on the list allowing to do so). This mechanism allows for representing uncertainties in fuel load configurations in a realistic way.

More detailed information on the functionality of the DFG can be obtained from Baker [51] and Wade and Robbins [53].

The description as given above applies to the development stage of the DFG as per January 2012 (B-RISK version 2012.0.2). More functions are likely to be added in the process of its further development.

3.1.6 Integration with the BRANZFIRE fire growth sub-model

The new radiative fire spread and DFG sub-models and the BRANZFIRE fire growth sub-model are integrated into B-RISK in such a way that the first ignited item as well as secondary ignited items can ignite wall and ceiling linings, analogously as described in Section 3.1.2. The following effects and limitations are connected with this functionality:

- Items in the vicinity of a corner but not touching a wall can ignite only one wall (the wall which is closer to the item), other than items which are placed directly in a corner (these ignite the two walls which join at the corner).

- There is no “shadow effect” if a non-burning item is located between a burning item and the wall. However it is likely that the non-burning item ignites earlier than the wall (depending on the ignition characteristics of the item and the wall), because it is closer to the burning item than the wall. Hence it would be able to ignite the wall in its turn.
- Only one item can ignite the walls or ceiling. If an item with a comparatively small HRR first ignites a lining and then another item with a much larger HRR (which could have ignited the lining in its turn as well), the flame spread on the wall will be governed by the HRR of the “smaller” item and might therefore be less intense than if it was ignited by the “larger” item.
- Burning walls and ceilings cannot ignite other items, because the wall and ceiling HRRs are not spatially defined. However they contribute to heating up the upper layer and the compartment boundaries, which in their turn contribute to the ignition of other items.

Wade [54] has updated the section about the fire growth sub-model from the BRANZFIRE Technical reference guide [24] so it reflects the current functionality of the fire growth sub-model within B-RISK.

3.1.7 Verification and validation

Extensive verification and validation data is available for the BRANZFIRE zone model (e.g. Wade [14] [23]). In particular the fire growth sub-model is validated against ISO 9705 room-corner experiments as mentioned in Section 1.6. B-RISK is under development and verification and validation are still in process. Baker et al. [55] have verified the radiative fire spread sub-model and compared it against experimental data, concluding that key parameters such as “the rate of growth to flashover, the average peak HRR and the duration of peak burning were all similar to that predicted by the DFG” (note that Baker et al. use the term “DFG” for describing both the radiative fire spread sub-model and the DFG sub-model as a whole, deviating from the practice in this report). Also Baker et al. [50] have found “good agreement … between the theoretical model and actual intermediate-scale experiments in the laboratory”. Further validation work is currently under way (e.g. by Fong [56] on the capability of B-RISK to model the transition phase to flashover).

3.2 Functionality tests of the fire growth sub-model

3.2.1 Introduction

The purpose of the functionality tests described in this section is to assess the following:

1. Are the BRANZFIRE fire growth sub-model and the new radiative fire spread and DFG sub-models integrated into B-RISK in such a way that deterministic runs from B-RISK produce the same or reasonably similar results as the same calculations performed in BRANZFIRE? If this is the case it is ensured that B-RISK is applicable for modelling fire spread on linings as well as BRANZFIRE is, with the latter being verified and validated for the purpose of modelling flame spread on linings as shown previously. The functionality tests hereto are described in Section 3.2.2.
2. Since the DFG places fuel items randomly in a room, fuel items as ignition sources for linings can be located directly against a lining or at a certain distance away from it. Is the fire growth sub-model sensitive to changes in the location of the ignition source as it would be expected to be? This is assessed by analysing ignition and flame spread on linings when
   - a burner is located at different distances from a wall or corner (the further the burner from the wall or corner, the later a lining should ignite).
   - different materials are used as a lining (different materials have different ignition properties and should ignite at different times if exposed to the same burner).

   The functionality tests hereto are described in Sections 3.2.3 and 3.2.4.

The functionality tests in Sections 3.2.3 and 3.2.4 are conducted with two different, non-fire retardant materials: 4 mm thick plywood and 18 mm thick MDF. Figure 3-1 shows their HRR in a cone calorimeter when exposed to a heat flux of 35 kW/m^2. Additionally, the HRR of fire retardant plywood is shown (plywood FR), because this material will be used in the final probabilistic simulations. “Plywood ordinary” is shown simply for illustrating the variety of HRR curves that are obtained from different wood derivatives and different thicknesses. The MDF data are from tests conducted by Li [57]; the plywood data are from the BRANZFIRE database [58]. (In this database, the thickness of the materials for which cone calorimeter data is provided is not shown; in the case of the plywood the thickness is mentioned in the material’s name and therefore known.) The HRRs from the cone calorimeter are used by the fire growth sub-model to calculate the flame spread on the linings. Therefore different compartment HRR developments should be expected from different burning lining materials. This can be analysed by means of the following functionality tests.

In Chapter 2, the time to reach flashover has been set as main criterion for the analyses in this study. It is therefore sensible to consider the time to flashover when analysing the functionality tests. Babrauskas and Jones [48] mention that a HRR of 1000 kW is a suitable conservative criterion for flashover in compartments similar to the ISO 9705 compartment. A HRR of 1000 kW is therefore used in this chapter as a flashover criterion for comparing flashover times in a simple but effective way.

The B-RISK version used for these functionality tests is 2011.0.28.

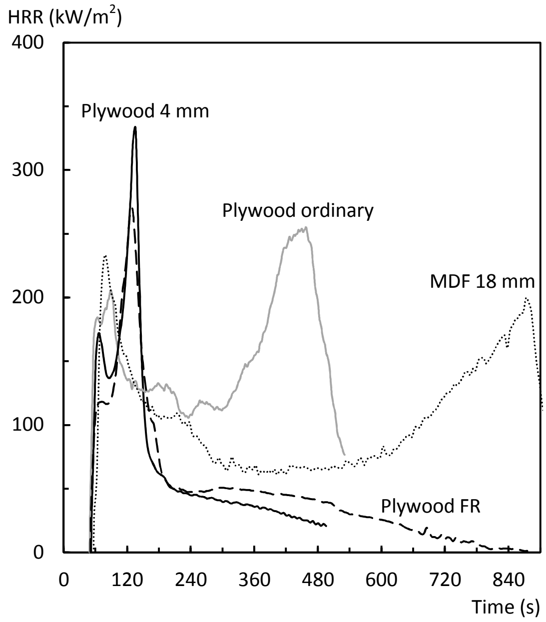


Figure 3-1 Heat release rates of different materials in cone calorimeter at 35 kW/m² incident heat flux

3.2.2 Integration of the fire growth sub-model into B-RISK

In this section, the results of deterministic calculations of the flame spread on linings for equal scenarios in B-RISK and BRANZFIRE are compared. The scenario is based on the ISO 9705 room-corner test and corresponds with verification case 4-2 of the BRANZFIRE validation data compilation [23]. A corresponding base model is included in the BRANZFIRE software package [58] (Ply104wall.mod, Ply104ceil.mod, and Ply104.mod). The results are shown in Figure 3-2, Figure 3-3, and Figure 3-4. Furthermore, in these figures the experimental data are shown which were used by Wade for validating the BRANZFIRE fire growth sub-model [23]. Note that the naming of the different scenarios follows the definitions in Table 2-1, i.e. Case B – walls and ceiling lined with combustible material, Case C – walls combustible, Case D – ceiling combustible. Plywood is used for this comparison only, since MDF was not used in the BRANZFIRE validation.

(Note that the BRANZFIRE curve in Figure 3-4 is slightly different from the curve in Wade's BRANZFIRE validation data compilation [23], Figure 17. This is due to the flame length power and the flame area constant which were changed in [23], Figure 17 for this particular curve only. No reason could be established in consultation with Wade. Flame length power and the flame area constant are here consistently to the other simulations. See Section 4.8 for more detail on these values.)

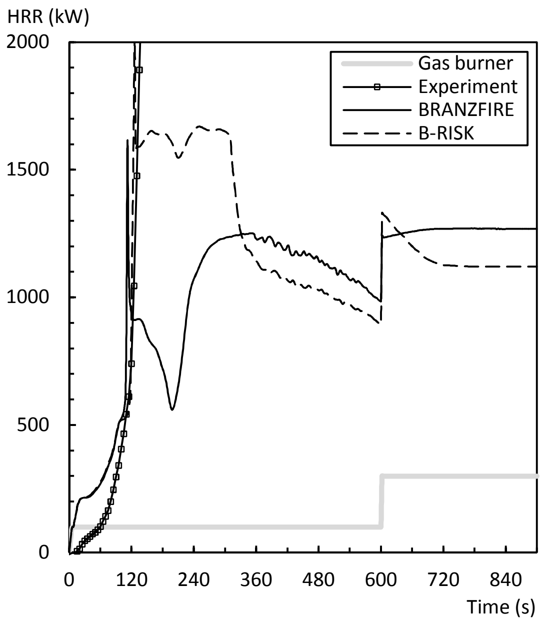


Figure 3-2 Heat release from wooden linings, plywood 4 mm, Case B, burner in corner

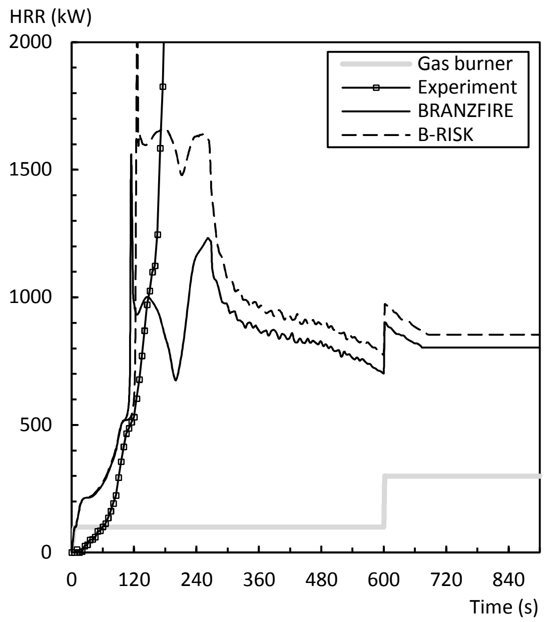


Figure 3-3 Heat release from wooden linings, plywood 4 mm, Case C, burner in corner

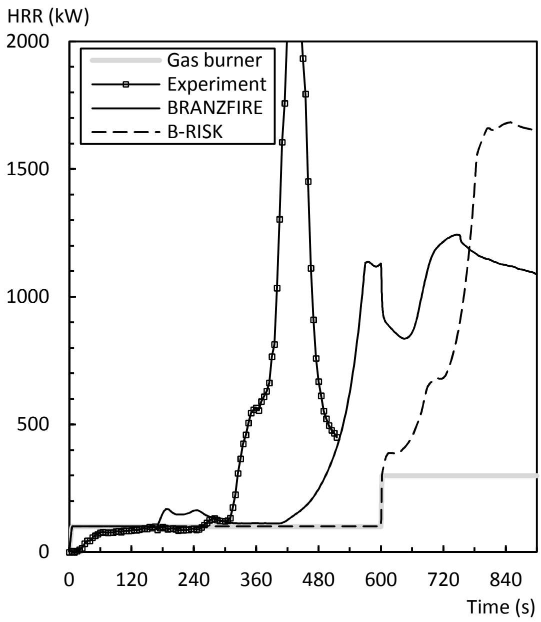


Figure 3-4 Heat release from wooden linings, plywood 4 mm, Case D, burner in corner

From Figure 3-2 and Figure 3-3 it can be seen that for the wall and wall/ceiling configurations B-RISK gives similar results to BRANZFIRE. The reason for the minor deviation between B-RISK and BRANZFIRE shortly before 120 s cannot be identified. However if comparing the flashover times (when the HRR reaches 1000 kW), the difference is negligible and also in close agreement with the experimental data. Somewhat bigger differences are observed for the ceiling configuration (Figure 3-4). The flashover time calculated with BRANZFIRE is about 140% of the experimental flashover time, and the flashover time from B-RISK even 200%. Note that the HRR in B-RISK increases only after the burner output is increased to 300 kW. No reason could be established for this difference; further investigation is necessary in order establish the reason for the deviation.

3.2.3 Moving a burner away from the corner

In this section, the way that the fire growth sub-model reacts to a burner at different distances from the corner is tested. The distance indications in the graphs are the distances in the *x*- and *y*-directions between the walls joining into the corner and the closest corner of the burner (Figure 3-5). For comparison, results of BRANZFIRE calculations and, where applicable, experiments are also given. This is possible only when the burner is directly in the corner, since in BRANZFIRE burners can be put only directly in the corner, against a wall or in the room centre (without the ability to ignite wall linings when located in the centre).

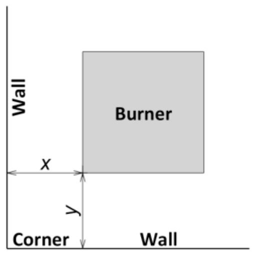


Figure 3-5 Illustration of distance indication from burner to corner/wall

Figure 3-6 is in principle the same as Figure 3-2, however it is supplemented with curves from B-RISK with the burner at different distances from the corner. It can be seen that the further away he burner is from the corner, the later the linings ignite and the slower the HRR growths. Note that B-RISK ignites only one of the two walls joining the corner if the burner is not directly in the corner as already explained in Section 3.1.6. The centre burners are not able to ignite the ceiling in the case of BRANZFIRE and the wall or the ceiling in the case of B-RISK respectively.

Figure 3-7 shows the same configuration as Figure 3-6, but with walls and ceiling lined with MDF instead of plywood. The burners 0.1 m and 0.3 m away from the corner are able to ignite the linings, but there is no significant flame spread on the lining during the observed period. The BRANZFIRE and B-RISK curves for the corner burner again deviate shortly before 120 s as observed previously on plywood linings. However, the difference in the flashover time is within approximately 50 s. As with the plywood linings, the centre burners do not ignite the linings.

When comparing Figure 3-7 with Figure 3-6 it can be seen that the ignition times of the MDF and plywood linings are almost the same, but the fire growth is more severe on the plywood linings. This is to be expected when the cone calorimeter HRRs of the two materials in Figure 3-1 are compared; the ignition times are similar but plywood reaches a much higher peak HRR than MDF shortly after ignition.

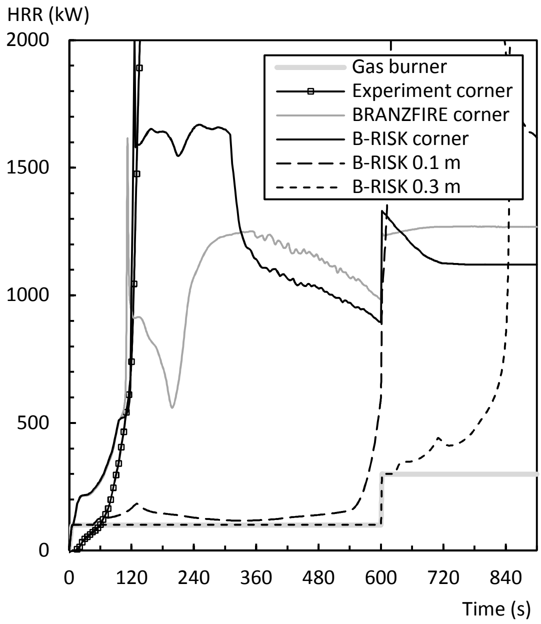


***Figure 3-6** Heat release from wooden linings, plywood 4 mm, Case B, burner at different distances from corner.*

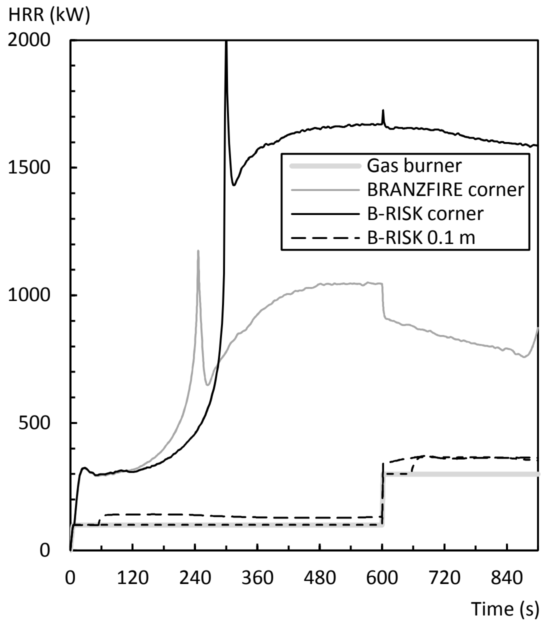


***Figure 3-7** Heat release from wooden linings, MDF 18 mm, Case B, burner at different distances from corner.*

Figure 3-8 and Figure 3-9 are the same scenarios as Figure 3-6 and Figure 3-7, but with the ceiling only lined with wooden material. Only the corner burners ignite the ceiling. If the burner is moved away from the corner, no ignition takes place. Figure 3-8 turns out to be the same as Figure 3-4 in the preceding section. As mentioned, there are quite significant differences in the flashover times between BRANZFIRE and B-RISK (and the experiment using plywood) for the ceiling only case.

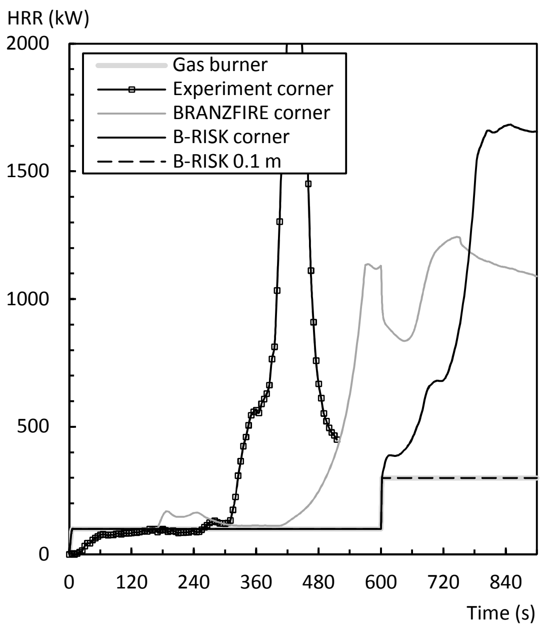


***Figure 3-8** Heat release from wooden linings, plywood 4 mm, Case D, burner at different distances from the corner.*

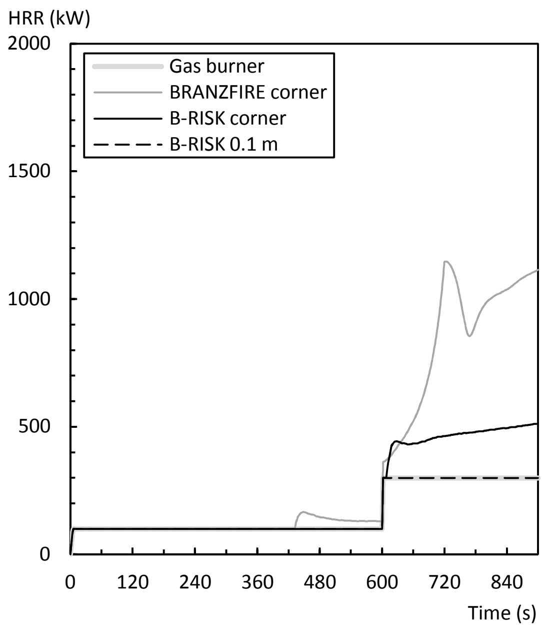


***Figure 3-9** Heat release from wooden linings, MDF 18 mm, Case D, burner at different distances from the corner.*

3.2.4 Moving a burner away from the wall

In this section the same analysis as in the previous section is done, except that the burner is moved away from the wall rather than away from the corner. The principle of the distance indications is the same as shown in Figure 3-5 but simply one-dimensional. Experimental data is not available for comparison.

Figure 3-10 clearly illustrates the effect of moving a burner away from the wall. Walls and ceiling are lined with plywood in this case. The curves B-RISK 0.1 m and B-RISK 0.3 m are the same as in Figure 3-6, because even when a burner is removed from a corner but with the same distance to two walls, only one wall is ignited. BRANZFIRE and B-RISK give almost identical results.

In Figure 3-11 the same configurations as in Figure 3-10 are analysed, but with MDF on walls and ceiling. The conclusions to be drawn are basically the same as they were for Figure 3-7 – almost identical ignition times as in Figure 3-10 but less intense fire growth. Again, the corresponding BRANZFIRE and B-RISK curves do not deviate significantly from each other.

Figure 3-12 and Figure 3-13 are the same scenarios as for Figure 3-10 and Figure 3-11, but with the ceiling only lined with wooden material. The only configuration in which the ceiling lining is ignited is the burner against the wall with the plywood lining in BRANZFIRE. In the corresponding B-RISK calculation, the ceiling does not ignite in the observed period.

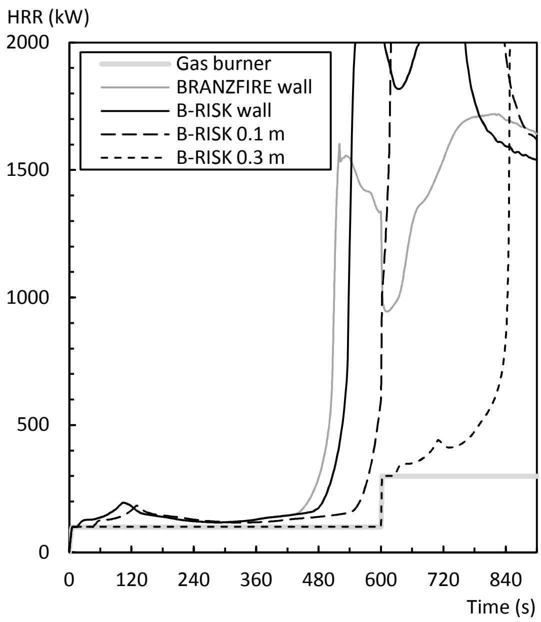


Figure 3-10 Heat release from wooden linings, plywood 4 mm, Case B, burner at different distances from the wall.

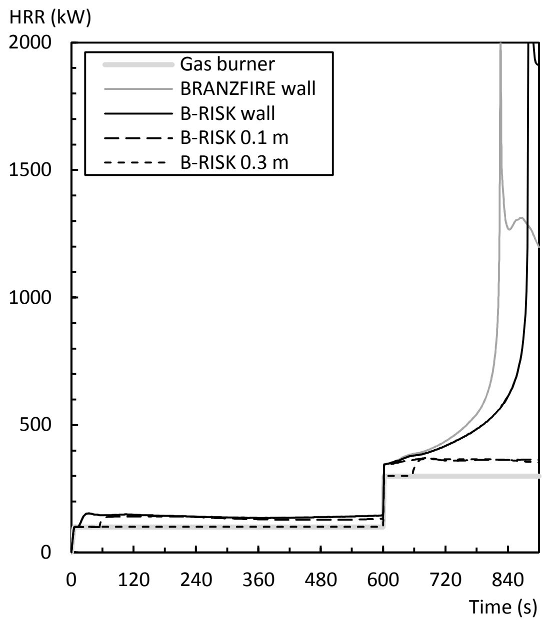


Figure 3-11 Heat release from wooden linings, MDF 18 mm, Case B, burner at different distances from the wall.

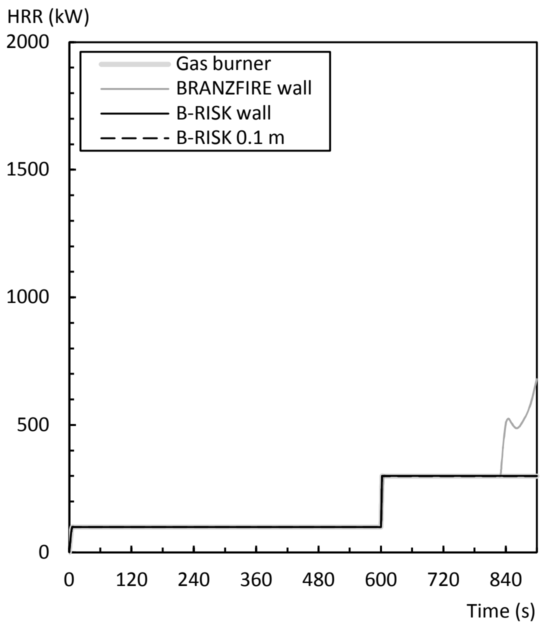


Figure 3-12 Heat release from wooden linings, plywood 4 mm, Case D, burner at different distances from the wall.

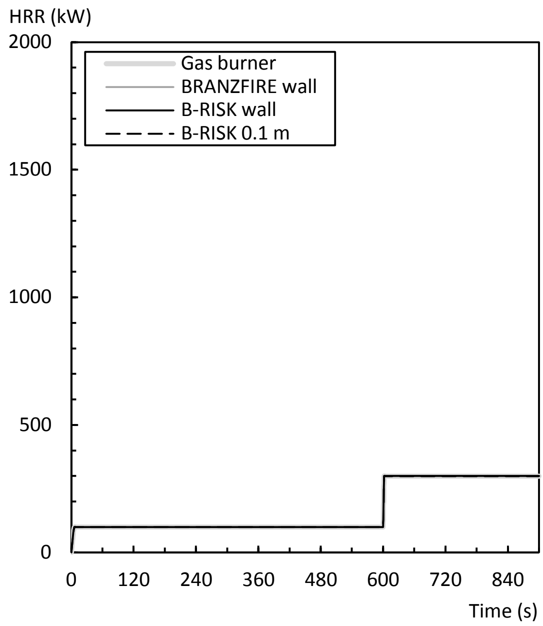
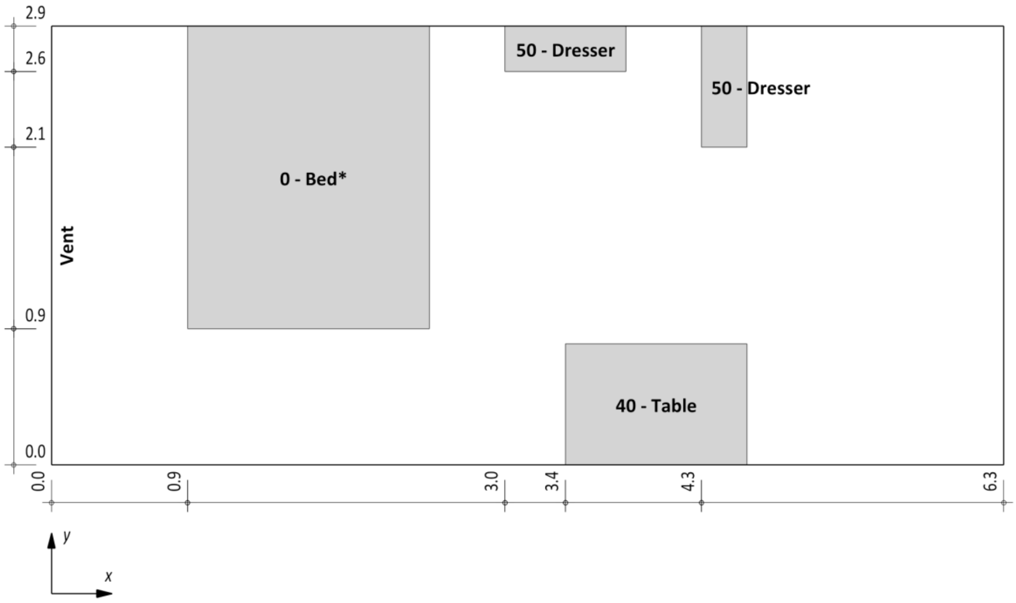


Figure 3-13 Heat release from wooden linings, MDF 18 mm, Case D, burner at different distances from the wall.

3.3 Comparison with experiments

Full scale tests of wooden modular hotel rooms were conducted in Switzerland to look at the efficiency of sprinklers in timber constructions (reported by Frangi and Fontana [4] and Maag and Fontana [45] respectively). In three of the experiments the sprinklers were not connected to the water supply so the fire could grow to flashover and beyond. In two of them, the walls and ceiling were lined with gypsum-plasterboard. In the third experiment, the walls were lined with OSB and the ceiling with multi-layer solid wood panel. Flashover times were recorded, which can be used to determine the capability of B-RISK to model flashover in compartments with non-combustible and wooden linings.

A layout of the compartment and the fuel items is given in Figure 3-14. The room was furnished equally in all experiments with a mattress and furniture mock-ups made out of wood pallets. The mattress was ignited with a fuel pan located under the mattress. Prior to the full scale tests a free burn test was conducted with a mattress similar to the mattresses used in the full scale tests in order to observe its burning behaviour. Unfortunately, no mass loss or HRR was measured. The HRR of the mattress as a burning item in B-RISK is estimated based on literature data therefore. Babrauskas [59] gives peak HRRs for mattresses, based on which the peak HRR is estimated. The growth phase is modelled as a fast t-squared fire growth (following Karlsson and Quintiere [44]). Details on the derivation of the HRR can be found in Annex A2 along with the other relevant fuel item properties of the mattress (fuel item 0). In the same way, the HRRs of the mock-up furniture have to be constructed. Correlations for pallet stacks given by Babrauskas [59] are used to estimate the peak HRR, and again the growth phase is modelled as a fast t-squared fire growth (following Karlsson and Quintiere [44]). More details are also given in Annex A2 (fuel items 40 and 50). General information on the relevance of the HRR and the derivation of all input values for B-RISK modelling are given in Chapter 4. All other model inputs are shown and explained in Annex A3 along with the simulation log files. 20 iterations are run, considering different values from distributions for ambient condition inputs.



Distance indications in m.
* First ignited item

Figure 3-14 Floor plan layout of modular hotel room experiments

The flashover times observed in the tests are compared in Table 3-1 with the flashover times simulated with B-RISK. Note that the experimental flashover times are adapted from the reference in a way that the time between ignition of the fuel pan and ignition of the mattress is not included. Flashover in the experiment was determined when flames emerged out of the window.

Table 3-1 Comparison of time to flashover between modular hotel room experiments and B-RISK

	Experiment	B-RISK
Non-combustible linings	ca. 270 s ca. 318 s	185–188 s
Wooden linings	ca. 167 s	40 s
Difference between wooden and non-combustible linings	ca. 103 s ca. 151 s	145–148 s

Table 3-1 shows that for the given configuration, B-RISK simulations result in about the same difference between flashover times for wooden and non-combustible linings as can be observed from the full scale experiments. In the experiments, the difference was ca. 103 s and 151 s. The difference in the simulations is ca. 146 s and lies therefore in the range of the observed differences in the experiments. The difference between experiment and simulation in the absolute magnitude of the flashover time can be explained with the fact that the HRR of the first burning item (mattress) is modelled with a t-squared fire growth without incipient phase, whereas the HRR of the mattress in the experiment might have had an incipient phase and a fire growth different from a t-squared growth. Unfortunately there is not enough detail available from experiments for modelling the mattress HRR more realistically.

The B-RISK version used for this comparison is 2012.0.7.

3.4 Conclusion

From the information provided in this chapter it can be concluded that

- fire growth on linings in B-RISK is similar to BRANZFIRE if the walls or the walls and ceiling are lined with wooden material.
- if the ceiling is combustible only, B-RISK under-predicts the lining fire growth and flashover times connected with it.
- lining fire growth in B-RISK is sensitive to location changes of burners and material changes as desired.
- Differences in flashover times in compartments with wooden and non-combustible linings are similar when predicted with B-RISK and observed in a full scale experiment.

B-RISK is therefore capable of modelling the fire growth on linings in connection with ignition sources (fuel items) in different locations if walls and ceiling are lined with a wooden material (Case B from Table 2-1) and if walls are lined with a wooden material (Case C from Table 2-1). The differences in calculated flashover times for rooms with wooden and non-combustible linings are in the range of what is observed in a real test. B-RISK can therefore be used as a tool for comparing flashover times in compartments with wooden and non-combustible linings considering uncertainties in the fuel load configurations for Cases B and C from Table 2-1. For Case D (ceiling only with wooden lining) it does not satisfactorily predict lining flame spread.

4 Model inputs

4.1 Introduction

In this chapter, the input values and distributions for the model in B-RISK are summarized and their derivation explained. Annex A4 gives sample input files of a simulation in xml-format for illustration. The descriptions in this chapter are based on B-RISK version 2012.0.3.

Some inputs, such as the fuel items, can in reality be different in different occupancies. Where necessary, inputs are orientated such as they would be in a hotel room scenario. This is because the used room size (ISO room-corner test compartment) is comparatively small and therefore suitable for a small compartmented occupancy like hotel rather than e.g. an office, which is often open-spaced. See Section 4.3 for the reasons for choosing this particular room size. Furthermore, a furnished hotel room can be used as representatively for any sleeping or living occupancy.

4.2 Ambient conditions

The inputs for ambient conditions (interior and exterior temperature, relative humidity) can be defined as distributions. The distributions used in this study are given in Table 4-1 and are estimated for Swiss conditions. The interior temperature distribution is estimated for a heated hotel room. The minimum temperature represents an unused room which is heated at a reduced level, and the maximum temperature represents a non-air-conditioned room during summer time. The mean value of the exterior temperature distribution corresponds to the yearly average temperature in Zurich/Switzerland. The lower bound represents a minimum outside temperature in winter time, and the upper bound considers the possibility of heated-up air at a building façade.

Table 4-1 Distributions for ambient condition inputs

Interior temperature	
Triangular distribution	
Most likely (°C)	22
Minimum (°C)	15
Maximum (°C)	30
Exterior temperature	
Normal distribution	
Mean (°C)	8
Variance (°C^2)	100
Lower bound (°C)	-15
Upper bound (°C)	45
Relative humidity	
Triangular distribution	
Most likely (°C)	50
Minimum (°C)	20
Maximum (°C)	75

The influence of the distributions on flashover times is investigated in a parametric study in Section 5.3.

4.3 Compartment boundaries

The values given in Table 4-2 below are used as inputs for the compartment geometry. The compartment geometry (including door opening vent) corresponds to the ISO 9705 room-corner test compartment (compare Figure 1-2). This is the configuration for which validation of the BRANZFIRE fire growth sub-model is documented (Wade [23]). Also, the lining materials (non-combustible: plasterboard; wooden: plywood) and the substrate are chosen in such a way that they correspond to the Cases for which validation is documented. Additionally, MDF is used for examining the influence of changes in the lining material. The properties of the lining materials and the substrate are given in Table 4-3. All data for plywood, plywood FR and plasterboard are available from the BRANZFIRE materials database [58]. The data for MDF is from Li [57]. For MDF, not all necessary data are available from experiments. Data from the BRANZFIRE materials database for "medium density fibreboard" are taken in such cases. This is reasonable since the density and conductivity are similar for the two materials. The cone calorimeter data for MDF are given in Annex A5.

Table 4-2 Room geometry inputs

Room length (m)	3.6
Room width (m)	2.4
Room height (m)	2.4
Vent width (m)	0.8
Vent height (m)	2.0
Vent sill height (m)	0.0

Table 4-3 Lining and substrate materials properties

	Substrate*	Non-combustible lining	Wooden linings		
	Plasterboard	Plasterboard	Plywood 4 mm	Plywood FR	MDF 18 mm
Density (kg/m^3)	810	810	580	550	720
Conductivity (W/mK)	0.16	0.16	0.12	0.12	0.15
Specific heat (J/kgK)	900	900	1215	2850	1260
Emissivity (-)	0.88	0.88	0.88	0.88	0.88 **
Minimum surface temperature for flame spread (°C)	0	0	164	164	160 **
Flame spread parameter (kW^2/m^3)	0	0	13	13	13 **
Heat of combustion (MJ/kg)	0	0	13.2	12.8	12.0 **
Soot yield (g/g)	0	0	0.015	0.015	0.015 **
H_20 yield (g/g)	0	0	0.442	0.442	0.442 **
CO_2 yield (g/g)	0	0	1.27	1.27	1.27 **
Thickness (mm)	16	16	4	4	18

* not applicable to floor (floor has lining only without a substrate)
** values from BRANZFIRE materials database [58], medium density fibreboard

4.4 Fuel items

4.4.1 Overview

As outlined in Section 3.1.4 a major input for B-RISK is the fuel items, based on which the radiative fire spread sub-module calculates fire spread. Also the list of fuel items is the resource from which the DFG populates the compartment (Section 3.1.5).

Table 4-4 gives an overview of the fuel items used in this study. Items are chosen which typically can be found in hotel rooms. In order to add variability to the fuel items list, several similar items are defined per “furniture type” (e.g. three different mattresses/loveseats for representing a bed), from which the DFG will be able to choose when populating a room. This process of definition of fuel items includes a certain degree of arbitrariness. It is attempted in this work to use items with different HRR characteristics (peak HRR, time to peak HRR) per furniture type.

Similar items are grouped and numbered in the same decade in Table 4-4. Items highlighted with an asterisk are used in the fixed fuel load configuration for the parametric studies in Chapter 5. Tables with detailed information on every item are given in Annex A2. These tables show the inputs in an order as required in the B-RISK input interface, plus an HRR graph for illustration and the calculated fuel load energy. In the following sections, general information on the definition and derivation of the fuel items properties (including HRR, maximum number permitted and probability near wall) are given.

Table 4-4 Overview of fuel items

Item No.	Description	Fuel load energy (MJ)	Peak HRR – time (s), HRR (kW)	Max. number permitted	Probability near wall
1	Wood frame loveseat	610	280, 1050	1	0.5
2 *	PU foam spring-core mattress	187	500, 1770	1	0.5
3	Cotton/PU mattress with boxspring	374	550, 540 **	1	0.5
10	“California foam” easy chair	387	1895, 2100	2	0.5
11 *	PS/plywood/PU easy chair	280	240, 960	2	0.5
12	Polyester/wood/PU easy chair	295	1020, 450	2	0.5
20	Metal frame chair with adjustable back	41	130, 240	2	0.5
21 *	Metal frame chair with PU cushions	48	230, 290	2	0.5
30	Metal wardrobe	79	30, 700	2	0.5
31	Particleboard wardrobe	1391	260, 1950	2	0.5
40	Table out of wood pallets	1050	162, 1223	2	0.5
41 *	Wooden desk	360	240, 640	2	0.5
50 *	Dresser out of wood pallets	700	149, 1030	2	0.5
51	Wooden dresser	433	420, 1780	2	0.5
60 *	European television set	162	320, 290	2	0.5
61 *	European washing machine	312	840, 330	2	0.5
70 *	Cotton/polyester curtain 64% pleated	11	45, 110	2	1.0
71 *	Wastebasket Yamada	16	18, 50	2	0.5
72	Wastebasket Mehaffey	2	13, 30	2	0.5
73 *	Hard suitcase	161	480, 120	2	0.5

* Item used in fixed fuel load configuration for parametric studies in Chapter 5

** First peak only; second peak has higher HRR

4.4.2 Geometry

The geometrical shape of the fuel items is defined as rectangular parallelepiped. The dimensions of the outer edges of the combustible parts of the modelled real item are taken as inputs. In cases where no information on the dimensions of an item is available, the geometrical shape is estimated based on typical real items. Detailed data and references for each item are given in the fuel items tables in Annex A2. Note that the length of an item does not necessarily have to be larger than its width – if items are placed manually, the length corresponds to the dimension of the item in the *x*-direction and the width in the *y*-direction (compare Figure 5-1). If items are placed by the DFG this does not matter because the DFG can place items orientated in both directions.

The geometrical shape is critical in B-RISK for the following reasons:

- it defines – together with the spatial arrangement of an item – the relationship between burning and secondary items, which is crucial for the radiation calculations of the radiative fire spread sub-model (see Baker et al. [50] for more detail).
- the average of the width and length of an item is used as “burner width” in the lining flame spread calculations. The burner width is used for calculating the flame height and the wall area first ignited; it also influences how fast a ceiling lining is ignited (see Wade [24] for more detail).

Apart from the geometrical shape, the elevation of an item can be defined – e.g. for a mattress or a device such as a TV which sit at a certain height above floor. Items cannot be “stacked” on top of each other in the current B-RISK versions.

4.4.3 Ignition data

As explained in Section 3.1.4, the FTP method is used for determining when a secondary item ignites due to burning of another item (piloted ignition) or radiation from compartment boundaries and the upper layer (auto ignition). Baker et al. [52] explain this method in detail and describe how the required values for FTP calculations can be derived from cone calorimeter test data. As an example they also give the relevant values of a foam-padding-fabric. These values are used in this study for all upholstered furniture, mattress, and curtain items.

For other materials, FTP data have to be obtained. FTP data for piloted ignition of a range of materials are compiled by the SFPE [60]. Data on auto ignition, however, is not readily available. Baker et al. [52] show a method for approximating auto ignition data which is used in this study for deriving data for different materials. The methodology is shown in Table 4-5 for the example of polypropylene. The details of the derivation of the FTP data for the other materials are given in the fuel item tables in Annex A2. Note that horizontal ignition data is used, for which the reasons are discussed by Baker et al. [52].

For items other than upholstered furniture, mattress, and curtain, the choice of materials followed two criteria: firstly the availability of piloted ignition data in the SFPE engineering guide [60], and secondly it was attempted to introduce as much variability as possible in terms of different materials. As an example, PP and PE were used for different wastebaskets, and softwood, chipboard and plywood for different furniture items.

Table 4-5 Derivation of FTP data for auto ignition adapted from Baker et al. [52]

Step	Description	Example for PP (Polypropylene)
1.	Obtain critical heat flux ($q_{\text{crit,pilot}}$), FTP limit ($\text{FTP}_{\text{pilot}}$) and FTP index ($n$) for piloted ignition (e.g. from SFPE [60])	$q_{\text{crit,pilot}}$ = 6.5 kW/m^2 $\text{FTP}_{\text{pilot}}$ = 8110 s(kW/m^2)^n n = 1.50
2.	Calculate critical heat flux for auto ignition $q_{\text{crit,auto}}$ using a ratio $q_{\text{crit,auto}}/q_{\text{crit,pilot}}$ = 2.4 (assuming $q_{\text{crit,pilot}}/q_{\text{min,pilot}} = q_{\text{crit,auto}}/q_{\text{min,auto}}$)	$\boldsymbol{q_{\text{crit,auto}}} = q_{\text{crit,pilot}} \times 2.4$ = 6.5 kW/m^2 × 2.4 = **15.6 kW/m^2**
3.	Assume same thermal thicknesses for piloted and auto ignition -> same FTP index for both ignition modes	***n* = 1.50**
4.	Calculate $t_{\text{ig,pilot}}$ at q = 120 kW/m^2	$t_{\text{ig,pilot}} = \text{FTP}_{\text{pilot}}/(q - q_{\text{crit,pilot}})^n$ = 8110 s(kW/m^2)$^{1.5}$/(120 kW/m^2 – 6.5 kW/m^2)$^{1.5}$ = 6.7 s
5.	Assume same ignition times for auto ignition ($t_{\text{ig,auto}}$) and piloted ignition ($t_{\text{ig,pilot}}$) at q = 120 kW/m^2	$t_{\text{ig,auto}} = t_{\text{ig,pilot}}$ = 6.7 s
6.	Calculate FTP_{auto} at q = 120 kW/m^2	$\mathbf{FTP_{auto}} = t_{\text{ig,auto}}(q - q_{\text{crit,auto}})^n$ = 6.7 s × (120 kW/m^2 – 15.6 kW/m^2)$^{1.5}$ **= 7154 s(kW/m^2)$^{1.5}$**

4.4.4 Heat release rate (HRR) and burning rate enhancement (BRE)

HRR curves for the fuel items are taken as the free burning HRR curves of real items obtained from literature. Free burning HRR curves are used because HRR curves including compartment effects are not readily available, and if they were, the compartment configurations would have to be generalized somehow. The curves are approximated with up to 12 data points for the B-RISK input in order to represent the original curves. The only exceptions from this are items 40 and 50 which were already used for the comparison of B-RISK with the modular hotel room experiments (Section 3.3). Because no HRR data is available for these items, the HRR was modelled with a t-squared fire growth. Nevertheless, these items are also used in the fuel items list, because they add variability in terms of growth rates, peak HRR, and fuel load energy.

Incipient phases are cut from the original curves, because it is not always indicated whether and how much of the incipient phase is considered in the literature source, and therefore it would not be possible to consider it consistently for all fuel items. Another reason is that secondary ignited items are not expected to show long stages of incipient burning (to be discussed later). Not considering incipient phases is reasonable for a comparative analysis; however one has to bear in mind that the absolute magnitude of resulting flashover times will not correlate with flashover times from experiments with real furniture (as shown in Section 3.3), since real compartment fires typically have an incipient phase (Figure 1-1).

See Annex A2 for detailed references in terms of the HRR curves of the single fuel items and information on whether incipient stages were cut.

Measuring HRRs of burning items is a complex topic and a field of research by itself. More discussion on the above HRR curves is required therefore, since they are a major, governing input for B-RISK analyses.

The HRR development of an item burning in a compartment is influenced by the following factors (adapted from Särdqvist [61]):

- the orientation and power of the ignition source influences whether an incipient stage takes place or not and how long it is.
- if an item burns in a compartment, re-radiation from hot layers and compartment boundaries can accelerate fire growth and cause higher peak HRRs than if burning freely (recalling that free burning HRR curves are taken as model input in this work).
- pre-heating prior to ignition can cause more intense burning (here of particular interest regarding secondary items).
- “disturbances” like vent flows can delay or accelerate ignition and flame spread on items.
- the orientation of the ignited surface (e.g. horizontally or vertically) has significant influence on the flame spread on an item.

These influences can be illustrated by considering a simple piece of wooden furniture with even surfaces, e.g. a bedside table. Different locations (e.g. laterally or on top) and different powers (e.g. candle flame or gas burner) of ignition sources would produce different HRRs once the bedside table has ignited. The HRR curves which are used for the single items in this study are for free burning situations with relatively small ignition sources – which can result in long incipient phases and relatively low growth rates for items like the exemplary bedside table. However, if a face of the bedside table was exposed to a large radiant heat source (e.g. a burning sofa close to it), much more intense burning would be expected soon after ignition, and the HRR would be rather similar to what can be observed from a wooden sample in the cone calorimeter (see Figure 3-1), i.e. a comparatively high, immediate HRR from the entire ignited face.

HRR curves of items in real fires can be significantly different from measured free burning HRR curves. This applies particularly to secondary ignited items. Two key issues can be extracted from the above listed influence factors on HRR curves of items burning in compartments:

1. compartment effects.
2. HRR curve of secondary ignited items.

For a single burning item, compartment effects can increase the peak HRR dramatically when compared to free burning. This effect is described in fundamental fire engineering literature such as by Drysdale [20]. If considering fire spread between items (as it is done in this study), a part of these compartment effects is represented by the model functionalities. The hotter the upper layer due to burning of an item, the faster secondary items will ignite and contribute to increasing the upper layer temperature. Thus there is an accelerating effect inherent in the model, although not explicitly for a single burning item. On the other hand, BRANZFIRE gives the possibility to consider compartment effects on a growing fire by specifying a burning rate enhancement (BRE). The effects of the BRE on flashover times are analysed in Section 5.4. Indeed, it is found that the BRE does not have a systematic influence on the resulting flashover times. Therefore the final simulations are run without considering BRE.

If looking at the HRR curve of secondary ignited items, there is no guidance available on how to consider the range of influence factors in a rational way. Babrauskas and Krasny [46] stated in the mid-eighties that “radiant augmentation of one burning item from another … is, conceptually, a simple process. Its quantification for actual furniture items, however, has not yet been attempted.” Nothing has changed in this respect – none of the available resources gives information on how to best model HRR curves of secondary ignited items. It is the only sensible way therefore to assume free burning HRR curves also for secondary ignited items. This is reasonable for a comparative study; however if the absolute magnitude of fire spread characteristics should be modelled, further research into this subject will be essential.

4.4.5 Radiant loss fraction

A radiant loss fraction of 0.3 is used for all items. This is in accordance with what Heskestad [62] recommends for cases “without specific knowledge”, and with what Frank et al. [63] use as a mean value for a radiant loss fraction distribution when analysing uncertainty in the calculation of sprinkler activation times.

At present time, no distributions can be defined in B-RISK for the radiant loss fraction of fuel items. A parametric study on the influence of changes in the radiant loss fraction on flashover times is conducted in Section 5.5.

Note that in the current versions of B-RISK a radiant loss fraction has to be defined for each single fuel item, as well as in the overall combustion parameters settings. According to Wade [64] both settings are used in different calculations, but in future versions the input in the combustion parameters settings should not be necessary anymore. It is sensible therefore to use for the time being the same radiant loss fraction value for all inputs.

4.4.6 Soot yield

Inputs of species yields are not a major issue for this study, since the interest is not in e.g. species concentrations at a certain time, but simply in the time to flashover. Soot yields, however, have an influence on the emissivity of the upper layer which again is used for calculating radiation from the upper layer on items.

Soot yields for different materials in well-ventilated fires can be obtained from Tewarson [65] as follows:

- Wood: 0.015 g/g.
- Synthetic solids: values from 0.011 g/g to 0.164 g/g, with the major part of the values between 0.06 g/g and 0.10 g/g.
- Flexible PU foams: median 0.196 g/g.

Since the fuel items in this study consist of these listed materials at proportions not further specified, an un-weighted average of 0.015 g/g for wood, 0.08 g/g for synthetic solids and 0.20 g for flexible PU foams is used which amounts to 0.098 g/g ≈ 0.1 g/g. This value is used as a fixed value for the pre-flashover stage.

4.4.7 Heat of combustion and mass

Heat of combustion and mass are important for this study because the DFG uses these values for calculating the actual FLED when populating rooms. Generally, heat of combustion values proposed for the calculation of fuel load densities by the International Fire Engineering Guidelines [66] are used in this study exactly for this purpose. In cases where values for heat of combustion are available from the same experiments as the HRR curve for the item, the experimental values are used. The used values and the materials assumed are specified in the fuel items tables in Annex A2. The mass is calculated then from the fuel load energy of the item (which results from the area under the HRR curve) and the heat of combustion. This mass might not be equal to the mass reported for a specific item, but this is sensible since the entire item is not always made out of combustible materials (e.g. a chair with a metal frame). Therefore the mass is not to be considered as a real measure, but rather as a calculated value of the combustible content.

Distributions could be assigned to the heat of combustion inputs, however this is not done in this study since the main parameter they influence is the actual FLED. The DFG provides sufficient variability in the fuel load configuration, and varying the heat of combustion values of single items would not contribute to a better representation of this uncertainty.

4.4.8 Maximum number of items and probability near wall

The DFG stops populating rooms if either the target FLED is reached, no more items fit into the room, or no more items are available from the items list (as described in Section 3.1.5). It has therefore to be defined how many pieces of every item the DFG should be allowed to use. In order to provide more flexibility and possibilities for the DFG to populate a room to the specified FLED, it is defined that two pieces of each item can be used per iteration, except for the large items mattress and loveseat, which are allowed to be used only once per iteration.

In connection with the quite extensive items list, it is possible and also occurs, that a room is populated with, say, 4 easy chairs and 4 chairs rather than with a mattress, an easy chair, a desk, and a chair. This is simply a limitation which has to be accepted at the current stage. Suggestions on how to make the DFG more flexible in this regard are given in Section 8.2.

Values of a probability for an item to be located against the wall are difficult to justify. It is arguable, that large items like beds (mattresses) are usually placed against a wall. However if a mattress starts burning, the probability that the burning happens at the wall is not 1, even if the mattress is placed against a wall. A value of 0.5 is assigned to the probability of being located against the wall for all items except for the curtain which has a probability of 1.0. Because of this, in every iteration about half of the items are located against the walls and, hence about half of the first ignited items are located directly against walls. It is analysed how changes in this input value influence the final results in Section 6.5.

4.5 Fuel load energy density (FLED)

The FLED is defined as the variable fuel load density per unit floor area. Target FLEDs and FLED distributions can be defined so that the compartment is “populated” by the DFG according to the specified value as explained in Section 3.1.5.

Flashover times are investigated using a FLED with a normal distribution based on the values proposed for hotel occupancies by the IFEG [66] – 300 MJ/m^2 as a mean value with a coefficient of variation of 40% (middle value of the proposed 30–50%; standard deviation: 120 MJ/m^2; variance: 14400 MJ^2/m^4).

Furthermore, the influence of the FLED on the flashover times for different lining configurations is analysed by using different target FLEDs. Since there are two exceptions (no more items available from the list/no more items fit into the room) for the DFG to terminate populating a room before achieving the target FLED, there is a “natural” upper FLED limit depending on the room geometry and the items list. It was found in preliminary simulations that, for the given configuration, this limit is approximately 500 MJ/m^2 (compare actual FLED histograms for Section 6.3 in Annex A9). This is why target FLEDs from 100 MJ/m^2 to 500 MJ/m^2 are used in the final simulations.

Due to the principles the DFG applies when populating a room (described in Section 3.1.5), the actual FLED may not reach the target FLED or exceed it to a different extent in every iteration. Histograms of the actual FLED inputs are given in Annex A9 for all simulations.

4.6 Simulation time

The simulation time is the duration which is modelled in a scenario. It has to be optimized in a way that satisfactory results are produced within the available time and computer resources. The simulation time, the number of iterations, and the output interval (time step over which output data is generated) depend on each other in terms of the required computer resources as discussed in the next section. The suitable simulation time for this study is discussed in this section.

Figure 4-1, Figure 4-2, and Figure 4-3 show the temperature developments in simulations of three different scenarios with 200 iterations each. Case names refer to the lining configurations according to Table 2-1. The sharp vertical lines indicate when 500 °C is reached and the iteration is terminated (flashover). The three figures represent the extreme cases in terms of target FLED and lining configurations. 1800 s is used as simulation time in the final simulations as a reasonable minimum duration with which practically all flashovers are covered (if looking at Figure 4-1, Figure 4-2, and Figure 4-3, only two out of 600 iterations would not be covered).

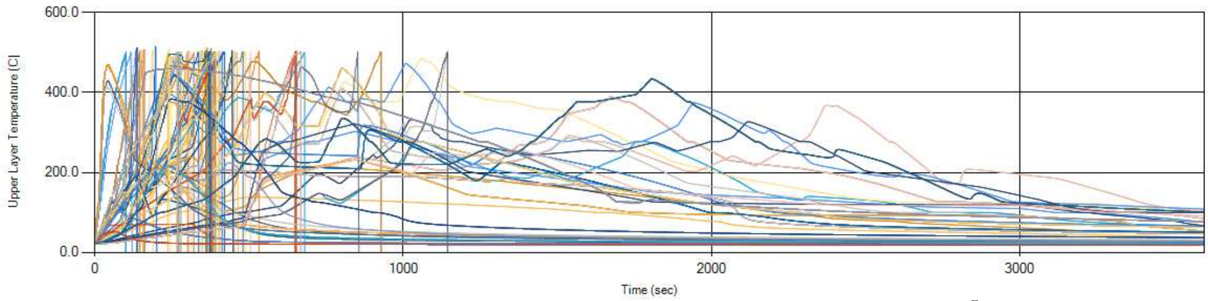


Figure 4-1 ***Upper layer temperature developments, Case A, target FLED = 100 MJ/m², 200 iterations (graph generated by B-RISK)***

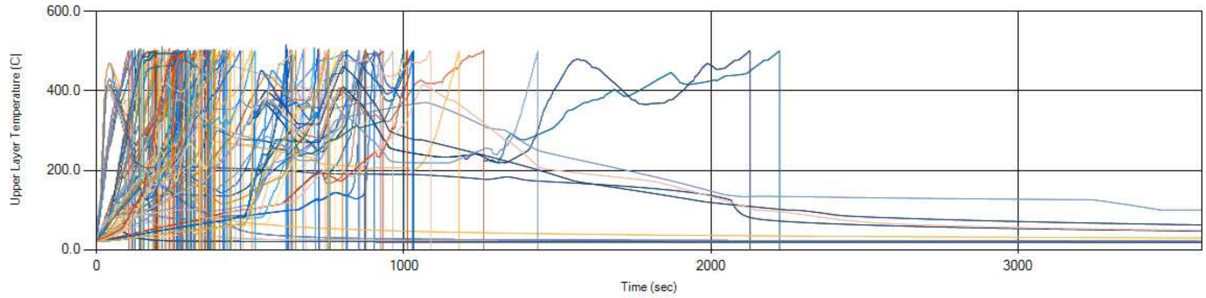


Figure 4-2 ***Upper layer temperature developments, Case A, target FLED = 400 MJ/m², 200 iterations (graph generated by B-RISK)***

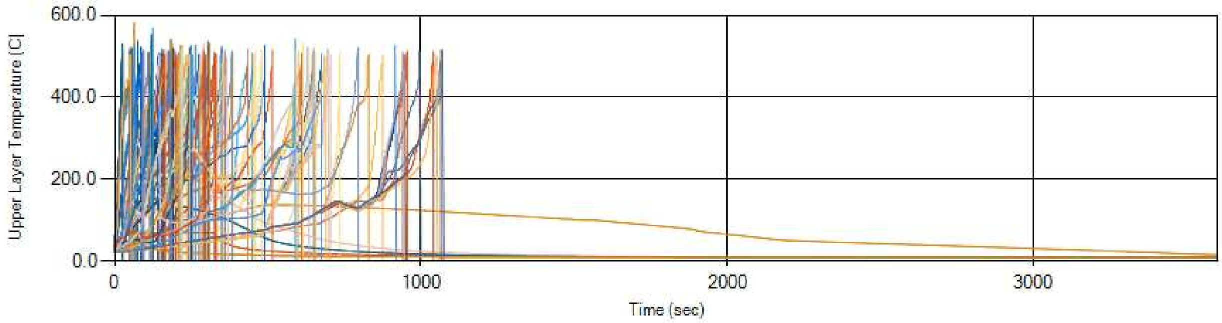


Figure 4-3 ***Upper layer temperature developments, Case B, target FLED = 400 MJ/m², 200 iterations (graph generated by B-RISK)***

4.7 Number of iterations

B-RISK runs multiple iterations per simulation, considering different values from input distributions and fuel load configurations from the DFG. Before running a simulation, a user has to consider how many iterations are required in order to produce results which satisfy the modelling purpose.

The more iterations that are performed, the higher the probability that extreme input values are considered and represented appropriately. Therefore, as many iterations as possible is desirable. On the other hand, the user wants to allocate capacities efficiently and therefore perform only as many iterations as necessary to produce satisfactory results.

The maximum possible number of iterations for this study is confined by computer capacities in processing the output data. Preliminary simulations have shown that with the given capacities (2 × 2.4 GHz processor, 2 GB RAM) an output data set of 800 iterations with a simulation time of 2000 s can be processed if a time step of 1 s is used as the output interval and linings are non-combustible. If wooden linings are involved, 400 iterations can be processed. If less iterations are run or the output interval is increased, a proportionally longer simulation time can be applied and vice versa. Approximately 180 iterations per hour are performed if linings are non-combustible and as little as 35 iterations per hour if wooden linings are involved.

One method of justifying the number of iterations is to demonstrate convergence in a way that the results of a simulation with *x* iterations is compared with the results of the same model in a simulation with 2 × *x* iterations and so on. When the results do not differ significantly anymore (e.g. less than a certain percentage), it can be claimed that the number of iterations is sufficient. In the following, this approach is applied for the same scenarios which were used in Section 4.6. 200, 400, 800, and 1600 iterations are performed. A histogram and a cumulative distribution of the flashover times is shown for each scenario (Figure 4-4 and Figure 4-5: Case A, target FLED = 100 MJ/m^2; Figure 4-6 and Figure 4-7: Case A, target FLED = 400 MJ/m^2; Figure 4-8 and Figure 4-9: Case B, target FLED = 100 MJ/m^2). Note that the bin sizes in the histograms are 60 s for flashover times up to 600 s, 300 s from 601 s to 1200 s, and 600 s from 1201 s to 2400 s. Table 4-6 summarizes different percentiles of flashover times from the three scenarios. Case names refer to the lining configurations according to Table 2-1.

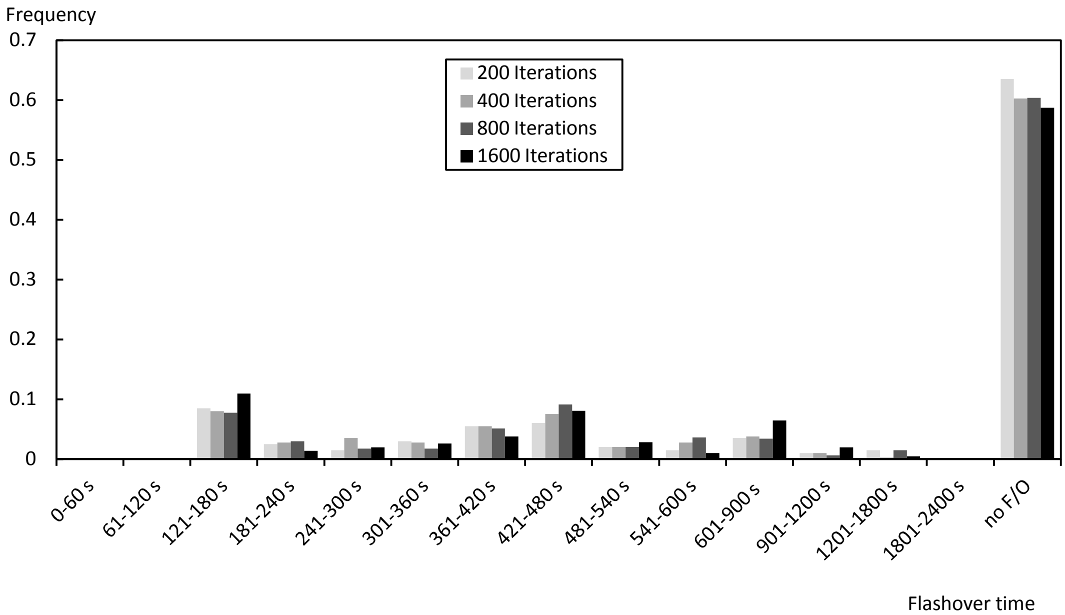


Figure 4-4 Flashover time histogram for different iteration numbers, Case A, target FLED = 100 MJ/m²

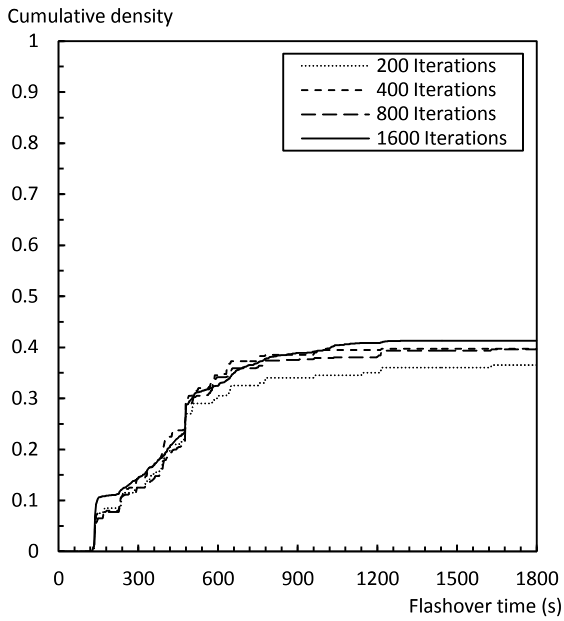


Figure 4-5 Flashover time cumulative densities for different iteration numbers, Case A, target FLED = 100 MJ/m²

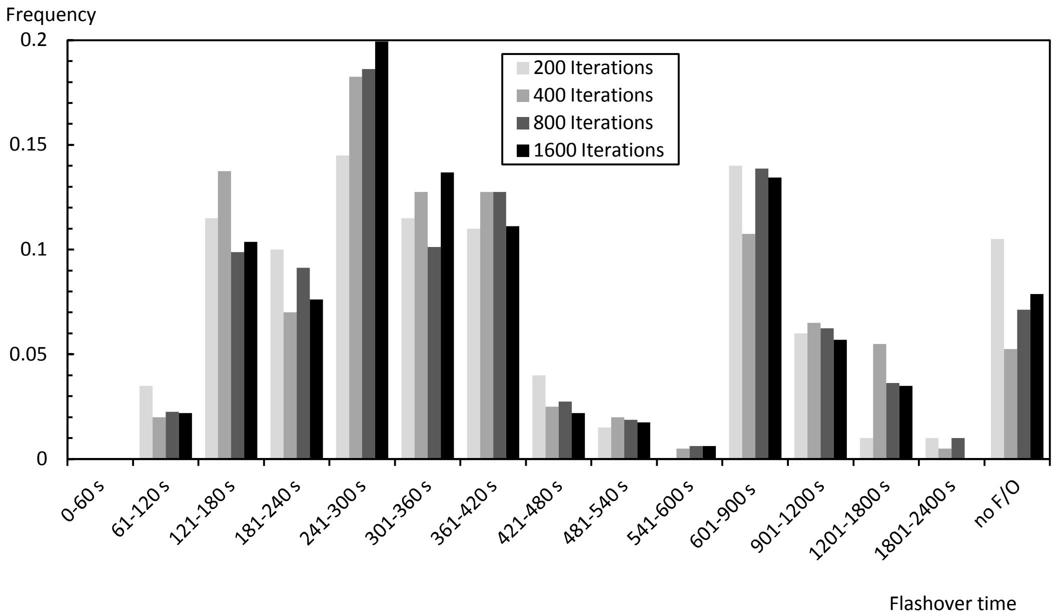


Figure 4-6 Flashover time histogram for different iteration numbers, Case A, target FLED = 400 MJ/m²

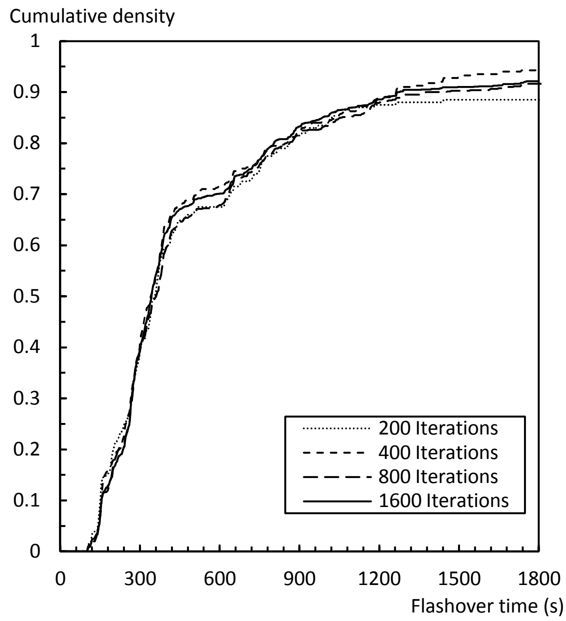


Figure 4-7 Flashover time cumulative densities for different iteration numbers, Case A, target FLED = 400 MJ/m²

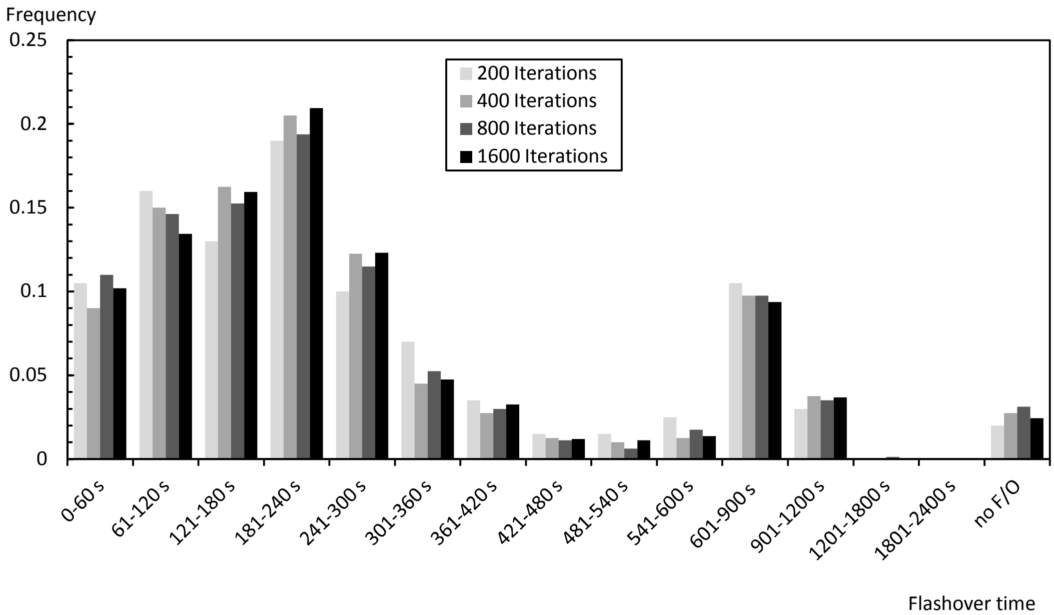


Figure 4-8 Flashover time histogram for different iteration numbers, Case B, target FLED = 400 MJ/m²

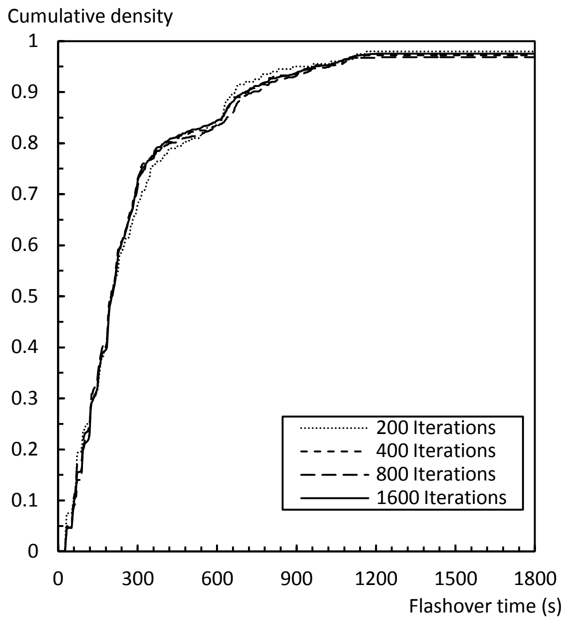


Figure 4-9 Flashover time cumulative densities for different iteration numbers, Case B, target FLED = 400 MJ/m²

Table 4-6 Probabilistic flashover times for different scenarios and iteration numbers

	Minimum	5th percentile*	50th percentile	Percentage flashed-over **
Case A, FLED = 100 MJ/m^2				
200 iterations	137 s	137 s	No flashover	37%
400 iterations	128 s	137 s	No flashover	40%
800 iterations	128 s	140 s	No flashover	40%
1600 iterations	127 s	137 s	No flashover	41%
Case A, FLED = 400 MJ/m^2				
200 iterations	105 s	141 s	353 s	90%
400 iterations	103 s	145 s	341 s	95%
800 iterations	102 s	144 s	360 s	93%
1600 iterations	102 s	146 s	346 s	92%
Case B, FLED = 400 MJ/m^2				
200 iterations	26 s	28 s	202 s	98%
400 iterations	26 s	53 s	198 s	97%
800 iterations	26 s	48 s	199 s	97%
1600 iterations	26 s	53 s	204 s	98%

* in 5% of the iterations flashover has occurred and in 95% of the iteration flashovers has not occurred

** Within 1800 s

A maximum number of iterations which can be computed in a reasonable time and of which the output data can be processed by B-RISK is 400; a simulation with wooden linings can take a little more than 10 hours, and simulations with non-combustible linings approximately 2 to 3 hours. 400 iterations are therefore executed for all scenarios of the final simulations.

The preceding graphs and Table 4-6 indicate the following degrees of precision if 400 iterations are performed:

- in terms of 5th percentiles: ± 5 s.
- in terms of 50th percentiles: ± 15 s.
- in terms of percentage of iterations in which flashover occurs: ± 3%.

These degrees of precision are indicative minimum values. In order to establish definite values, more simulations with higher numbers of iterations would be necessary.

Note that the above described simulations were conducted as preliminary simulations, and not all input data is consistent with what is described in the preceding Sections 4.2 to 4.6. Namely for the scenario Case A, target FLED = 100 MJ/m^2, the entire fuel items list was not used, but only 10 typical hotel room items as they are also used for the parametric studies in Chapter 5. This resulted in an interesting effect which is discussed here. Referring back to Figure 4-5, the cumulative density curves are not as smooth as they are in the other two scenarios. For example, a step in the curve is quite distinctively visible after approximately 500 s. Because of the low target FLED (100 MJ/m^2), relatively few items are placed in the room and the distances between the fuel items are relatively large, so there is less item-to-item fire spread than at higher target FLEDs. Therefore flashover times are governed by the single items' HRRs rather than by cumulative HRRs from different items. Obviously item 2 (see Annex A2) causes the step in Figure 4-5 at 500 s. The HRR of this item grows relatively slowly, until it spikes up to over 1.5 MW at 500 s. If item 2 is first ignited, its HRR is too small and/or other items are located too far in order to get involved and accelerate fire growth during the first 450 s. After 500 s flashover occurs solely due to item 2. So in practically every iteration where item 2 is first ignited, flashover occurs at 500 s. This is the case in approximately 10% of the iterations, since there are 10 items which can be ignited first. In the other two scenarios, there are more items available from the list and more items are placed in the room, so the cumulative distribution curves become less dependent on single items and are therefore smoother.

The B-RISK versions used in this section are 2012.0.2 for the scenario case A, target FLED = 100 MJ/m^2, and 2012.0.3 for the other two scenarios.

4.8 Other model options

B-RISK requires inputs and settings for conducting simulations additionally to the inputs discussed in this chapter. They are given in the following along with references to more detailed information within this report or elsewhere:

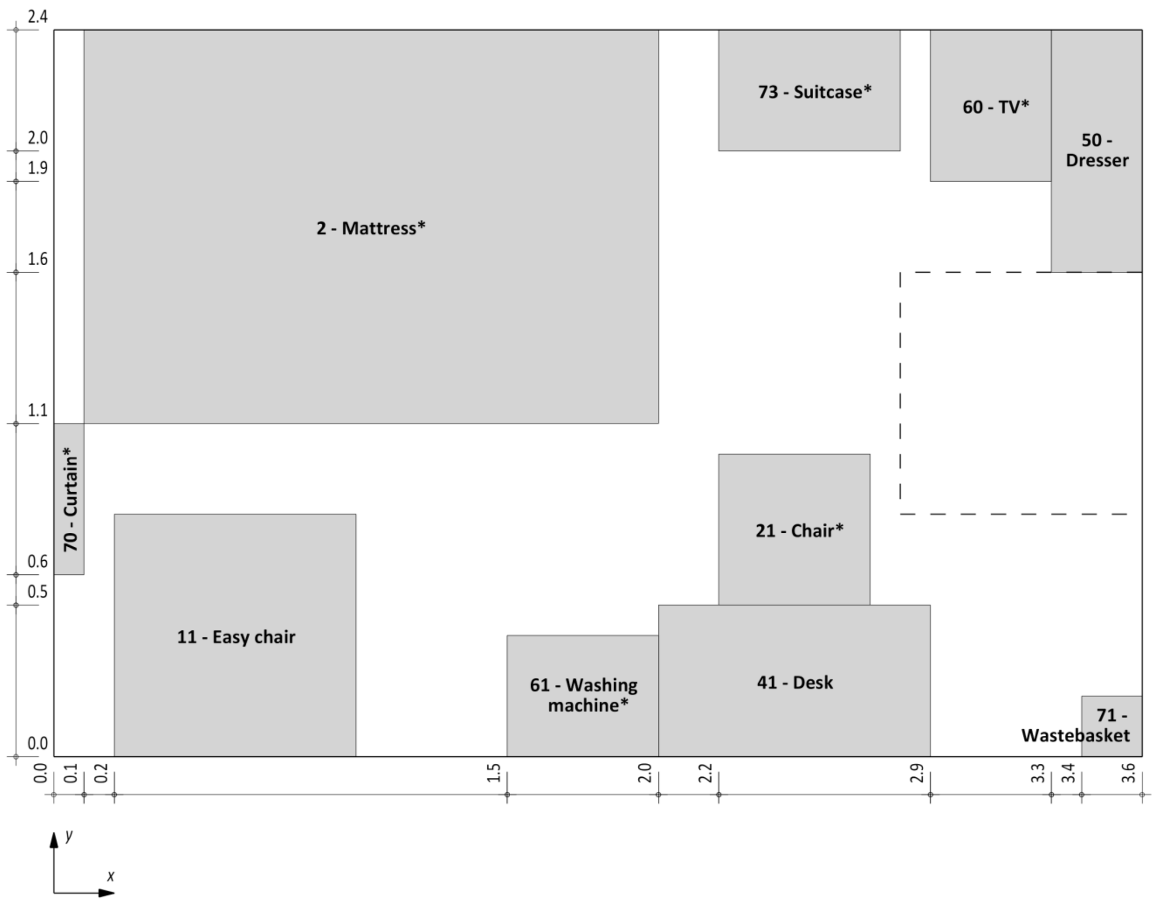
- DFG grid size: 0.1 m (see Wade and Robbins [53] for detail information).
- DFG vent clearance: 0.8 m (same as door width, Table 4-2).
- Plume model: McCaffrey (see Wade [24] for more detail).
- Fire growth on linings:
    - ignition correlations: FTP (see Section 3.1.2).
    - flame length power: 1.00 (value given by Wade [24]).
    - flame area constant: 0.0065 (value given by Wade [24]).
- Flashover criterion: upper layer temperature 500 °C (see Sections 2.3 and 5.3).
- Output interval: 1 s (in order to be able to present results at 1-s-steps, see Section 4.7).
- Iterations terminated at flashover.

5 Parametric studies

5.1 Introduction

In the foregoing chapters it has been explained how B-RISK works (Section 3.1) and what model inputs are used for this study (Chapter 4). It has also been shown that B-RISK is able to model fire spread from items to linings and flame spread on linings (the latter comparably to BRANZFIRE except for rooms with wooden linings on the ceiling only – see Section 3.2).

As mentioned in Section 3.1.7, Baker et al. [55] have validated the radiative fire spread sub-model for a single scenario with 9 items. The purpose of this chapter is to show that B-RISK is able to model fire spread within complex fuel configurations and to wooden linings. This is done based on a fixed fuel load configuration as shown in Figure 5-1. The configuration consists of 10 fuel items (actual FLED: 259 MJ/m^2) and is similar to what can be found in a hotel room of this size. The model is run with this fixed configuration 10 times, each time with another item first ignited. Different fire spread developments and flashover times are therefore expected for each of the 10 scenarios.



Distance indications in m. Dotted line: vent clearance area.
* Elevated items. See Annex A2 for detail.

Figure 5-1 Floor plan with fixed fuel load configuration for parametric studies

In Section 5.2, flashover times are shown for these characteristic scenarios with wooden and non-combustible linings, without changing any input values. In the sections that follow, different input values are varied in order to analyse how sensitive the resulting flashover times are to these values. While this kind of sensitivity analysis is not conducted on the probabilistic flashover times (considering different fuel configurations), there are still 10 characteristic ways of fire spread involved in the analysis. It can therefore be concluded that if a model input value does not have significant influence on these 10 deterministic runs, no significant influence on the probabilistic simulations is to be expected.

It is not the purpose to verify or validate the fire spread sub-model with these analyses. This is currently being done by others as mentioned in Section 3.1.7. It is solely the aim to understand how B-RISK works, whether it produces plausible results for certain configurations and what the influence of single model inputs is on the results.

The ability of the DFG to populate rooms randomly is not examined in any detail. Sample layouts of fuel load configurations generated by the DFG are given in Annex A6, which indicate that the DFG works as desired.

Case names refer to the lining configuration and correspond with Table 2-1. Refer to Table 4-3 for the lining materials properties; plywood is used for wooden linings. All other inputs correspond with the information given in Chapter 4, unless otherwise stated.

The B-RISK version used for this chapter is 2012.0.7, except in Section 5.4, where version 2012.0.3 is used.

5.2 Wooden vs. non-combustible lining

In Figure 5-2 the flashover times are compared for when the linings are non-combustible (Case A) and when walls and ceiling are lined with plywood (Case B) for different items that are the first to be ignited. For the ambient condition inputs, either the most likely or mean values (whichever is applicable) are used from Table 4-1 instead of distributions.

As expected, flashover times are mostly significantly shorter in Case B than in Case A due to the involvement of the linings in the fire growth. The fire growth developments can be traced in the simulation log files in Annex A7, showing the order in which items and linings get ignited.

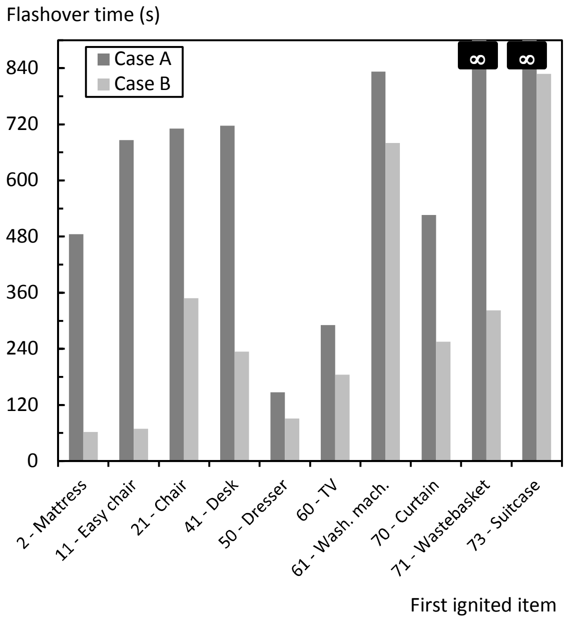


Figure 5-2 Flashover times in Cases A and B. No flashover occurs when items 71 and 73 are the first to be ignited in Case A.

5.3 Flashover criterion and ambient conditions

In this parametric study, flashover times are compared when flashover is determined according to two different criteria – 20 kW/m^2 irradiation at floor level and 500 °C temperature of the upper layer. 20 iterations are run for every item first ignited in order to attain a range of outputs representing the uncertainty in terms of the ambient condition input distributions (Table 4-1).

Figure 5-3 and Figure 5-4 show the resulting flashover times. The height of the bars indicates the time to flashover calculated with the applicable ambient condition inputs from Table 4-1, as was explained above. The error bars show the range of results of the 20 iterations due to the ambient condition input distributions. Note that the order of the items on the *x*-axis is not the same in the two graphs. The items are ordered according to the flashover time from the 500-°C-criterion. This is sensible since it is not the purpose to compare Figure 5-3 with Figure 5-4 (i.e. Case A with Case B as done in Section 5.2), but the flashover times from the two criteria and the influence of the ambient conditions' distributions on them.

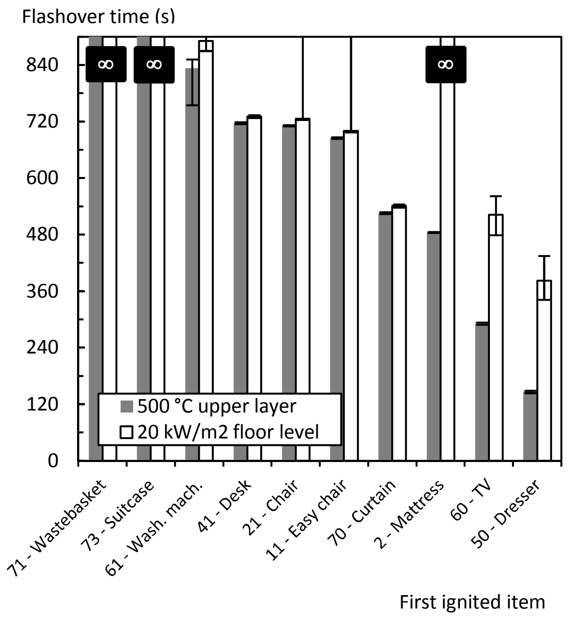


Figure 5-3 Flashover times from two criteria, Case A. Error bars indicate uncertainty in ambient conditions.
Upper range values outside graph:
Item 61, 20 kW/m²: 916 s
Item 21, 20 kW/m²: ∞ (no flashover)
Item 11, 20 kW/m²: ∞ (no flashover)
No flashover occurs when items 71 and 73 are the first to be ignited and for the 20-kW/m²-criterion when item 2 is the first to be ignited.

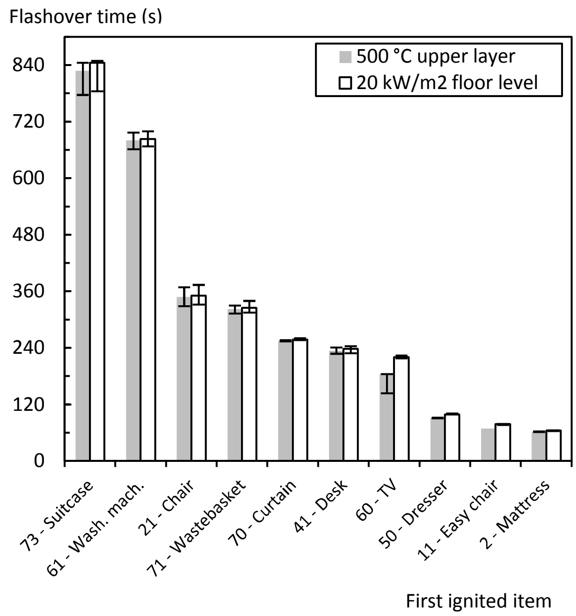


Figure 5-4 Flashover times from two criteria, Case B. Error bars indicate uncertainty in ambient conditions.

In terms of times to flashover there is no significant difference between the two flashover criteria in Figure 5-4. In Figure 5-3, significant differences in the flashover times for the different criteria can be seen when items 2, 60, and 50 are first ignited. The detailed model outputs show that the temperature of the upper layer is much higher than 500 °C when the 20-kW/m^2-criterion indicates flashover in these cases. A graph with detailed output information for the particular case when item 2 is first ignited is shown in Annex A8. It can be seen that the radiation at floor level does not reach 20 kW/m^2 even when the upper layer temperature exceeds 600 °C and the HRR exceeds 1500 kW. The reason for this is not investigated here. It is simply concluded that flashover times from the 20-kW/m^2-criterion are less consistent than from the 500-°C-criterion, especially in Case A.

The 500-°C-criterion is used for all further analyses and the final simulations therefore. In terms of ambient conditions, it is concluded that the uncertainty they cause is almost immeasurable at short flashover times and generally does not exceed ± 10% (considering the 500-°C-criterion), with the exception of item 60 in Figure 5-4 (– 22%). Either the most likely or mean values from Table 4-1, whichever is applicable, are used in the following analyses, whereas the distributions are used in the final simulations.

5.4 Burning rate enhancement (BRE)

The BRE is an option in B-RISK to consider compartment effects on the fire growth as explained in Section 4.4.4. Figure 5-5 and Figure 5-6 show the effect when BRE is considered. Either the most likely or mean values, whichever is applicable, are used instead of distributions for the ambient condition inputs (Table 4-1).

When requiring B-RISK to consider BRE, input values for a fuel heat of gasification and a fuel surface area have to be provided. Instead of specifying a fuel surface area, the user can let B-RISK estimate it based on the HRR of the fire and a user-defined mass loss per unit area. The latter option is used for this parametric study.

Heat of gasification values for different materials can be obtained from Tewarson [65] as follows:

- Corrugated paper: 2.2 kJ/g.
- Wood (Douglas fir): 1.8 kJ/g.
- Flexible PU foams: 1.2–2.7 kJ/g.

A value of 2.0 kJ/g is used for the heat of gasification representing an un-weighted average of corrugated paper and wood and a median value for flexible PU foams.

For defining a mass loss per unit area, the following values were considered:

- Wood: 1.0 mm/min × 500 kg/m^3 × 1/60 = 0.008 kg/s/m^2
  (1.0 mm/min is a charring rate according to EN 1995-1-2 [67], representing e.g. plywood, wood panelling, or solid wood beams and columns; 500 kg/m^3 is the density of a typical wood species such as spruce according to Kolb [2]) .
- Flexible PU foams: 0.021–0.027 kg/s/m^2 (from Tewarson [65]).

A value of 0.016 kg/s/m^2 is used for the mass loss per unit area representing an un-weighted average of wood combined with the median value for flexible PU foams.

In Case B (Figure 5-6), no influence from the BRE can be observed on the flashover times. In Case A (Figure 5-5), the differences are insignificant except when item 73 and item 11 are first ignited. When item 73 is first ignited, a borderline effect can be observed: without BRE, the first ignited item (suitcase) is not able to ignite other items. However with BRE, its heat release is high enough to ignite a secondary item, which causes the upper layer temperature to grow to flashover. When item 11 is first ignited without BRE, the upper layer temperature reaches almost 500 °C at approximately 220 s, but then decreases, until another item ignites and 500 °C is reached at 700 s. If BRE is considered, the temperature reaches 500 °C after 220 s.

As a result, BRE is not considered in the final simulations, because:

- it has practically no effect on flashover times, except for the two described borderline cases.
- assumptions would have to be made which contribute to the complexity of the model without adding to the quality of the results.

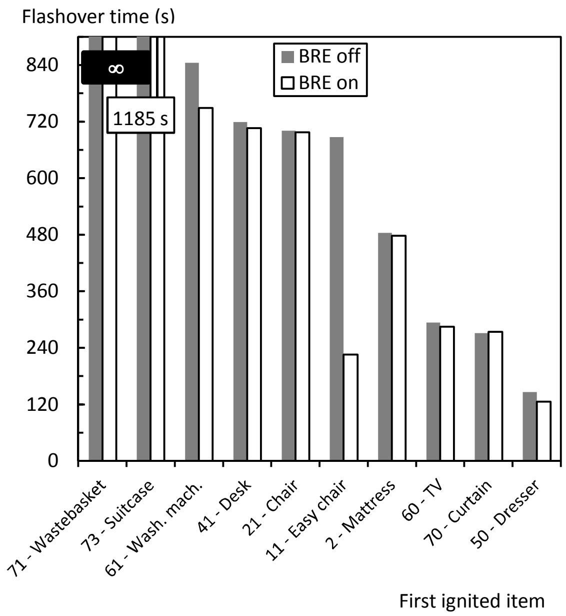


Figure 5-5 ***Effect of burning rate enhancement in Case A. No flashover occurs when item 71 is the first to be ignited and when item 73 is the first to be ignited without BRE.***

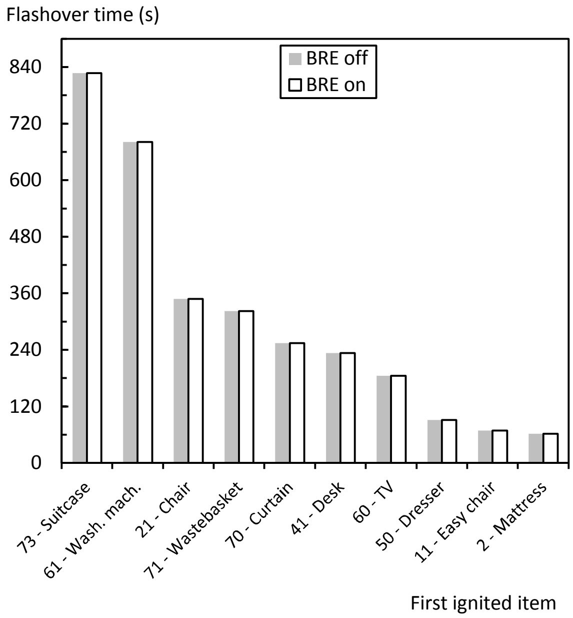


Figure 5-6 ***Effect of burning rate enhancement in Case B***

5.5 Radiant loss fraction

In this parametric study the influence of changes in the radiant loss fraction of the HRR on the flashover times is analysed. Radiant loss fractions have to be defined for every single fuel item and also for overall combustion parameters settings (see Section 4.4.5 for more detail).

The error bars in Figure 5-7 and Figure 5-8 show the influence on flashover times when the radiant loss fraction is changed to 0.25 and 0.35 respectively. The bar height indicates the flashover time when using a radiant loss fraction of 0.30. Either the most likely or mean values, whichever is applicable, are used instead of distributions for the ambient condition inputs (Table 4-1). Depending on the mechanisms in fire spread, a lower radiant loss fraction can cause longer flashover times (when several items are involved in fire growth and fire spread between items is important therefore) or shorter flashover times (when the HRR of one item governs the flashover time and fire spread between items is not important therefore). In particular cases, both higher and lower radiant loss fractions cause shorter flashover times (item 61 in Figure 5-7 and item 73 in Figure 5-8). When item 73 is first ignited in Case A (Figure 5-7), the same borderline effect occurs as already observed in Section 5.4. The suitcase is not able to ignite other items with a radiant loss fraction of 0.30, however changing the radiant loss fraction to 0.35 enables it to ignite other items and the fire eventually to grow to flashover. If linings are involved in fire growth, the influence of different radiant loss fractions is less important. For short flashover times (less than 200 s) the influence of different radiant loss fractions is almost immeasurable.

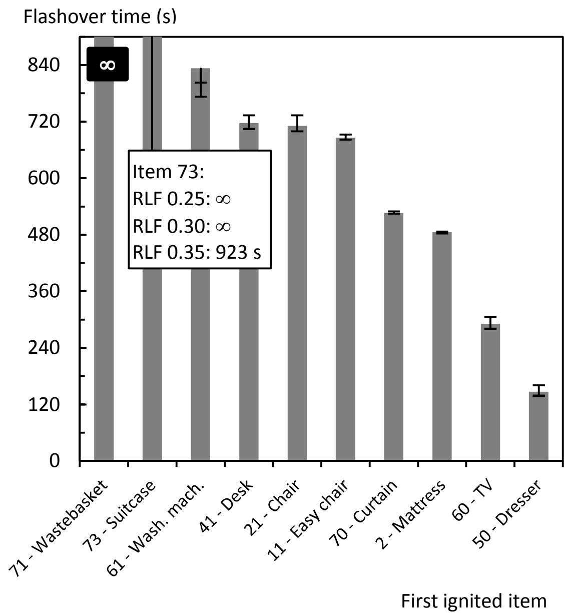


Figure 5-7 Effect of varying the radiant loss fraction (RLF) (0.25/0.30/0.35) in Case A.
No flashover occurs when item 71 is the first to be ignited and when item 73 is the first to be ignited with a radiant loss fraction of 0.25 and 0.30.

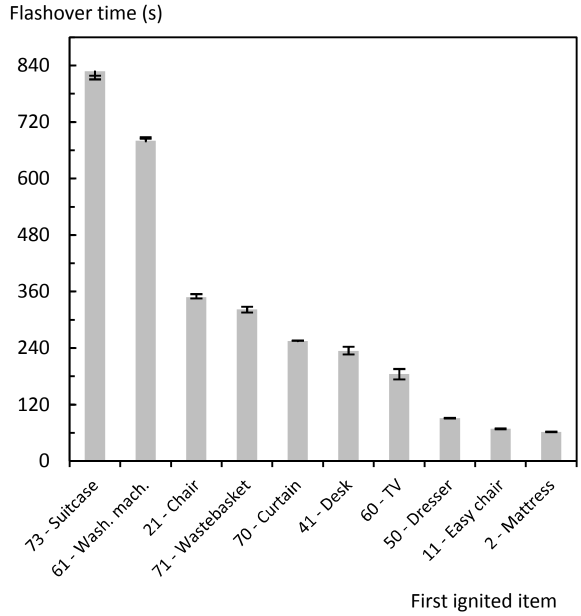


Figure 5-8 Effect of varying the radiant loss fraction (0.25/0.30/0.35) in Case B

6 Simulations and results

6.1 Introduction

This chapter shows the results of the final simulations and discusses them. Section 6.2 shows the base cases. Base cases have the following standard model inputs:

- FLED with a normal distribution and a mean value of 300 MJ/m^2.
- Lining materials: plasterboard and, where applicable, plywood.
- Probability of fuel items to be located against the wall: 0.5.

Sections 6.3 to 6.5 show how changes in input parameters influence the time to flashover. Input changes include different target FLEDs (Section 6.3), different lining materials (Section 6.4), and different probabilities of the fuel items to be located against a wall (Section 6.5). Case names refer to the lining configuration and correspond with Table 2-1. More detail on the above and all other model inputs is given in Chapter 4. Sample input files are shown in Annex A4.

The flashover times of each simulation are shown as cumulative density graphs. Characteristic values of the probabilistic flashover times are summarized in tables for each simulation. These are:

- *Minimum (time to flashover)*: The shortest time to flashover out of 400 iterations. This value is purely indicative, but not considered in discussions.
- *5th percentile*: The time after which in 5% of the iterations flashover has occurred and in 95% of the iterations flashover has not occurred. 5th percentiles (or 95th percentiles) are often used as design values in probabilistic design methods (e.g. for material strengths and characteristic loads in structural design at normal temperatures, Buchanan [6]).
- *50th percentile*: The median time to flashover from 400 iterations.
- *Percentage flashed-over after 1800 s:* The percentage of iterations where flashover occurs within the simulation time. Since it has been shown that flashover occurs after 1800 s in isolated cases only (Section 4.6), this percentage can be considered as proportion of fires in which flashover occurs at all.
- *Percentage flashed-over after 900 s*: The percentage of iterations where flashover occurs within 900 s. 900 s is the performance standard for fire services in Switzerland to arrive at a fire site after reception of an alarm [70].

Histograms of the actual FLEDs used in the simulations as well as time-series plots for the upper layer temperature and the HRR are given in Annex A9.

The B-RISK version used for the final simulations is 2012.0.9.

6.2 Base Cases A, B, and C

As mentioned in the previous section, the base cases have the standard modelling inputs regarding FLED (normal distribution, mean value 300 MJ/m^2), linings (plasterboard and, where applicable, plywood), and the fuel items' probability to be located against a wall (0.5). In Case A all linings are plasterboard, in Case B walls and ceiling are lined with plywood, and in Case C the walls only are lined with plywood (Table 2-1).

Figure 6-1 shows the cumulative density plot of the flashover times for the base Cases A, B, and C. Table 6-1 summarizes the probabilistic flashover times for each simulation.

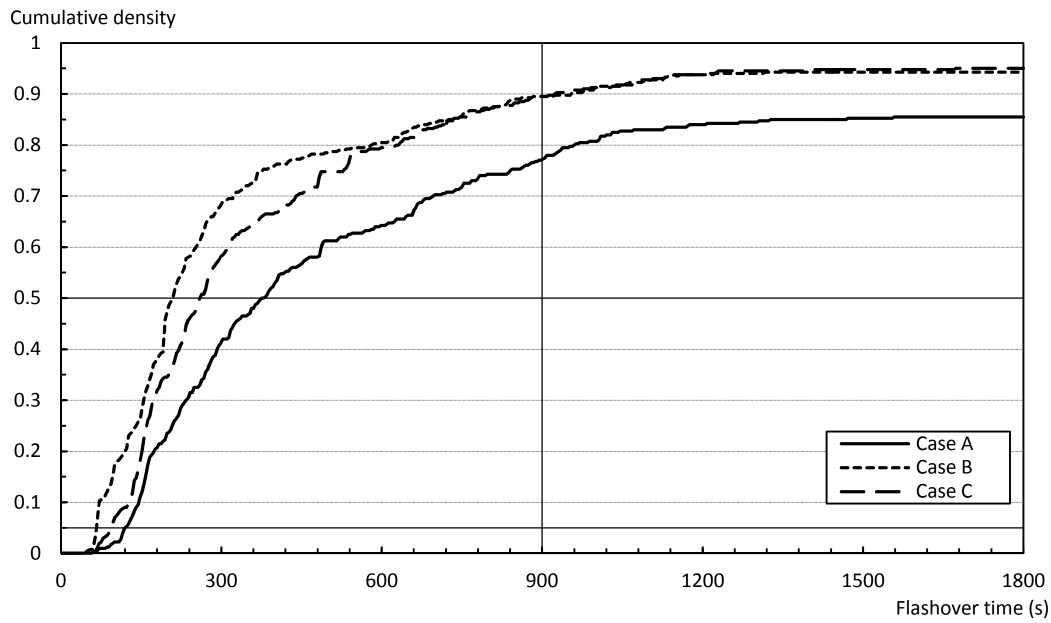


Figure 6-1 Flashover time cumulative densities for base Cases A, B, C

Table 6-1 Probabilistic flashover times for base Cases A, B, C

	Minimum	5th percentile	50th percentile	Percentage flashed-over 900 s	Percentage flashed-over 1800 s
Case A	61 s	119 s	375 s	77%	86%
Case B	46 s	65 s	207 s	90%	94%
Case C	58 s	95 s	259 s	90%	95%

The difference in the 5th percentiles is 54 s between Case A (non-combustible linings) and Case B (walls and ceiling plywood), with Case C (ceiling only plywood) approximately in the middle. The same structure is observed with the 50th percentiles, however the difference between Cases A and B is 168 s, and Case C is slightly closer to Case B than to Case A. In terms of percentages flashed-over, Cases B and C are almost identical (90% after 900 s and 95% after 1800 s). In Case A, significantly less flashovers occur (77% after 900 s and 86% after 1800 s).

6.3 Varying the target fuel load energy density (FLED)

This section shows the effect on flashover times when the FLED is changed. Simulations are performed with target FLEDs of 100/200/300/400/500 MJ/m^2. These target FLEDs are “single” target values without distribution, in contrary to the base case which is modelled with a FLED distribution with a mean value of 300 MJ/m^3 (see Section 4.5 for more detail). Figure 6-2 shows the cumulative density plots of the flashover times in comparison to the base case for Case A, Figure 6-3 for Case B, and Figure 6-4 for Case C.

Table 6-2, Table 6-3 and Table 6-4 summarize the relevant probabilistic flashover times.

Note that actual FLEDs generated by the DFG are “distributed” around the target FLED, although no distributions are specified. This is due to the principles the DFG applies when populating a room (see Section 3.1.5). Histograms of the actual FLEDs, mean values and coefficients of variation are given in Annex A9.

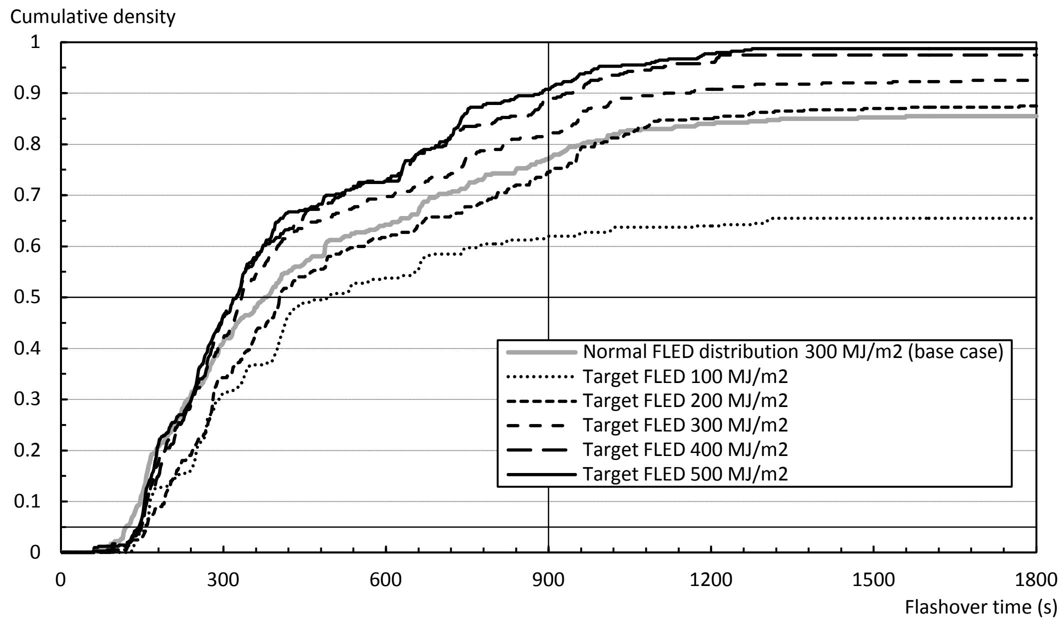


Figure 6-2 Flashover time cumulative densities for different FLEDs in Case A: FLED normal distribution, mean value 300 MJ/m^2 (base case), and target FLEDs from 100 MJ/m^2 to 500 MJ/m^2

Table 6-2 Probabilistic flashover times for different FLEDs in Case A: FLED normal distribution with mean value 300 MJ/m^2 (base case), and target FLEDs from 100 MJ/m^2 to 500 MJ/m^2

	Minimum	5th percentile	50th percentile	Percentage flashed-over	
				900 s	1800 s
FLED normal distribution 300 MJ/m^2 (base case)	61 s	119 s	375 s	77%	86%
Target FLED 100 MJ/m^2	129 s	154 s	492 s	62%	66%
Target FLED 200 MJ/m^2	95 s	158 s	403 s	75%	88%
Target FLED 300 MJ/m^2	92 s	144 s	333 s	82%	93%
Target FLED 400 MJ/m^2	57 s	148 s	322 s	89%	98%
Target FLED 500 MJ/m^2	58 s	143 s	322 s	91%	99%

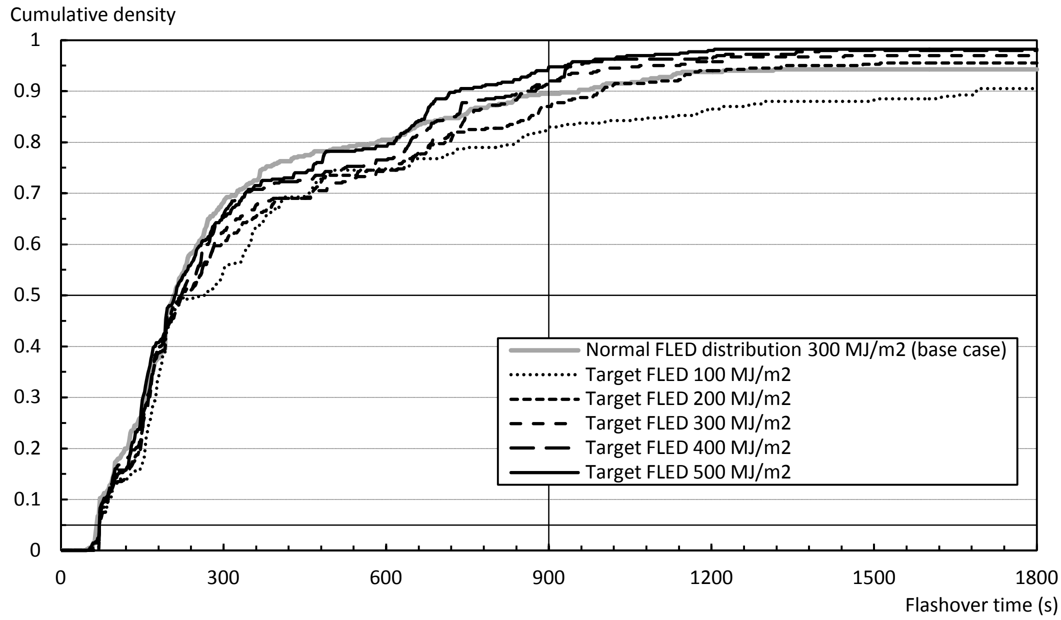


Figure 6-3 Flashover time cumulative densities for different FLEDs in Case B: FLED normal distribution, mean value 300 MJ/m² (base case), and target FLEDs from 100 MJ/m² to 500 MJ/m²

Table 6-3 Probabilistic flashover times for different FLEDs in Case B: FLED normal distribution with mean value 300 MJ/m² (base case), and target FLEDs from 100 MJ/m² to 500 MJ/m²

				Percentage flashed-over	
	Minimum	5th percentile	50th percentile	900 s	1800 s
FLED normal distribution 300 MJ/m² (base case)	46 s	65 s	207 s	90%	94%
Target FLED 100 MJ/m²	55 s	70 s	259 s	83%	91%
Target FLED 200 MJ/m²	70 s	70 s	219 s	87%	96%
Target FLED 300 MJ/m²	53 s	70 s	235 s	92%	97%
Target FLED 400 MJ/m²	54 s	70 s	221 s	92%	98%
Target FLED 500 MJ/m²	53 s	70 s	210 s	95%	98%

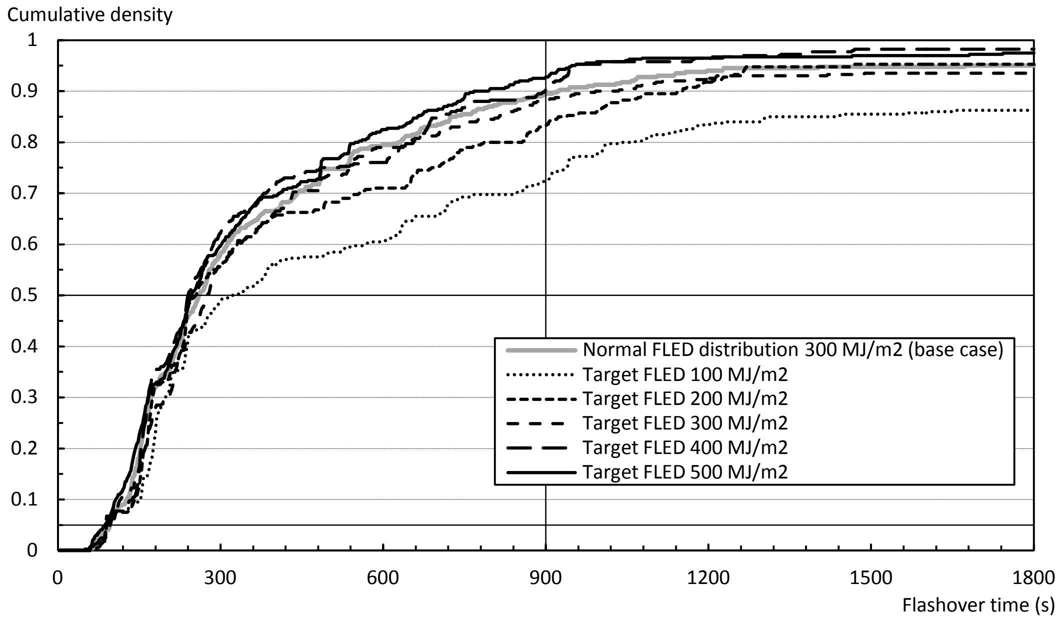


Figure 6-4 Flashover time cumulative densities for different FLEDs in Case C: FLED normal distribution, mean value 300 MJ/m^2 (base case), and target FLEDs from 100 MJ/m^2 to 500 MJ/m^2

Table 6-4 Probabilistic flashover times for different FLEDs in Case C: FLED normal distribution with mean value 300 MJ/m^2 (base case), and target FLEDs from 100 MJ/m^2 to 500 MJ/m^2

				Percentage flashed-over	
	Minimum	5th percentile	50th percentile	900 s	1800 s
FLED normal distribution 300 MJ/m^2 (base case)	58 s	95 s	259 s	90%	95%
Target FLED 100 MJ/m^2	54 s	88 s	321 s	73%	86%
Target FLED 200 MJ/m^2	60 s	89 s	253 s	83%	95%
Target FLED 300 MJ/m^2	49 s	96 s	274 s	88%	94%
Target FLED 400 MJ/m^2	53 s	88 s	239 s	90%	98%
Target FLED 500 MJ/m^2	56 s	86 s	247 s	93%	98%

Figure 6-5, Figure 6-6, and Figure 6-7 show compiled probabilistic flashover times of the above described simulations and emerging trends. From Figure 6-5 it can be seen that the FLED has no influence on the flashover time 5th percentiles. Regarding the median flashover times (50th percentiles), no significant influence can be seen if the FLEDs are 200 MJ/m^2 or higher in Cases B and C; only a FLED of 100 MJ/m^2 causes longer median flashover times. A clear trend toward longer median flashover times is observed in Case A when the FLED is lower than 300 MJ/m^2.

In terms of the percentage of fires in which flashover occurs within 900 s, a strong influence of the FLED is observed (Figure 6-6). The influence is the stronger where less wooden linings are involved (i.e. the strongest in Case A).

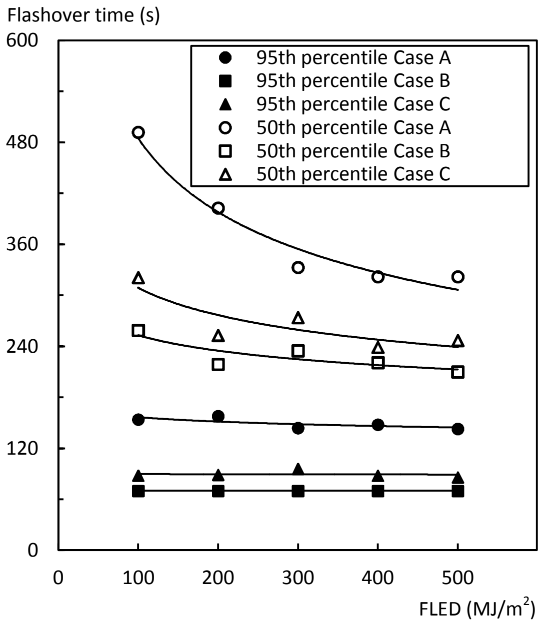


Figure 6-5 Flashover time vs. FLED trends

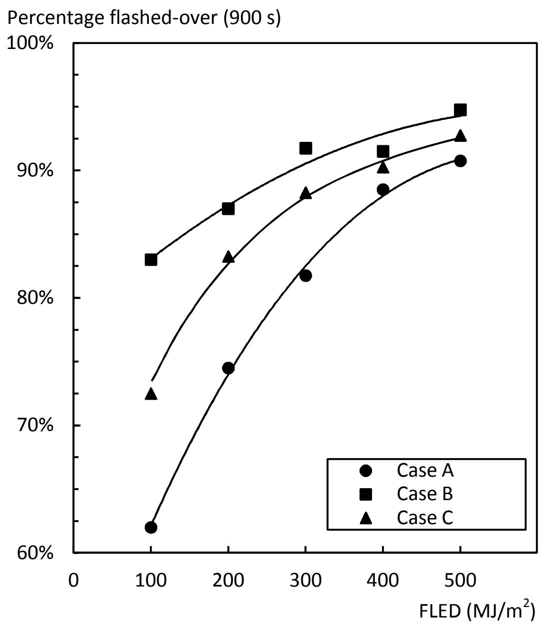


Figure 6-6 Percentage flashed-over after 900 s vs. FLED trends

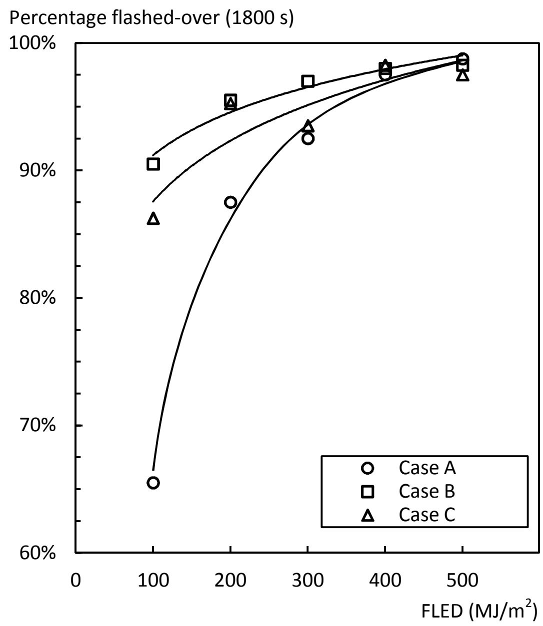


Figure 6-7 Percentage flashed-over after 1800 s vs. FLED trends

Different FLEDs have also a significant influence on the percentage of fires in which flashover occurs at all (i.e. within 1800 s, Figure 6-7). If comparatively high FLEDs are present (400–500 MJ/m^2), this percentage is 98–99% for all cases, indicating that flashover nearly always occurs regardless of whether the linings are wooden or not. However, if the FLED is lower (100–200 MJ/m^2), significantly less flashovers occur if all linings are non-combustible.

Differences between Cases B and C are generally small and practically negligible (i.e. slightly higher than or within the degrees of precision discussed in Section 4.7), except in the percentage of flashovers after 900 s in the single case when the FLED is 100 MJ/m^2.

6.4 Varying the wooden lining material

This section shows the effect on time to flashover when the wooden lining material is changed. Only Case B, where the walls and ceiling are lined with wooden materials, is analysed. Base case inputs are used for the FLED (normal distribution with a mean value of 300 MJ/m^2). Fire retardant plywood and MDF are used for comparison with the base case (non-fire retardant plywood). The lining material properties are described in detail in Table 4-3. Figure 3-1 shows the HRR of these materials in a cone calorimeter test.

From Figure 6-8 and Table 6-5 it can be seen that the differences in the probabilistic flashover times for the different materials are just slightly higher than or within the degrees of precision discussed in Section 4.7 and therefore are insignificant. Regarding the fire retardant plywood it should be noted that the effect of the used retardant was relatively low. Referring to Figure 3-1 it can be seen that the ignition time is the same and the peak HRR is only 20% lower for the fire retardant plywood if compared to the non-fire retardant plywood.

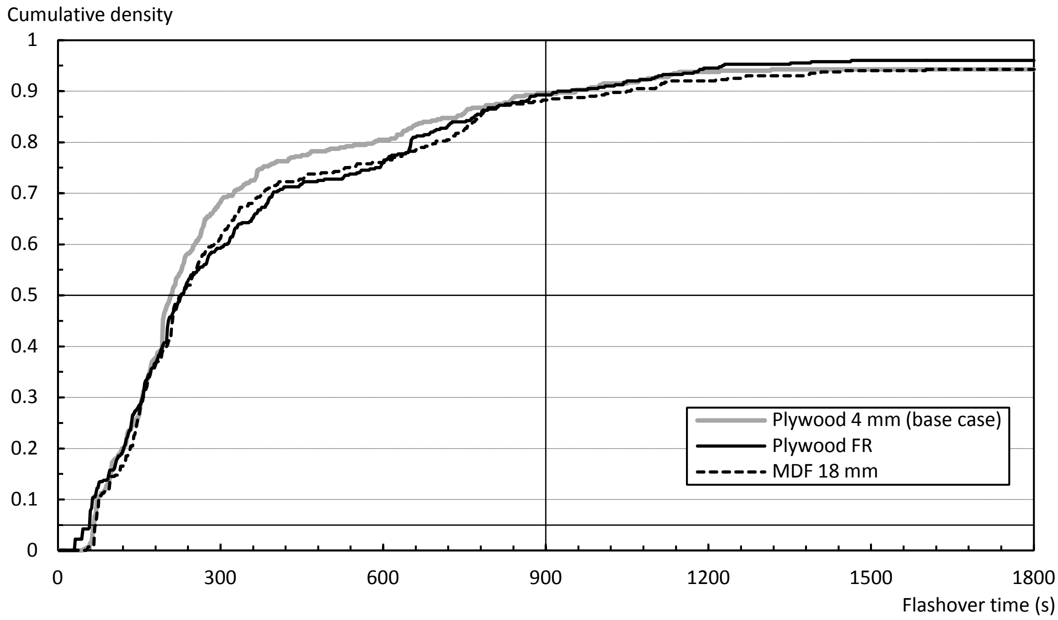


Figure 6-8 Flashover time cumulative densities for different wooden lining materials in Case B

Table 6-5 Probabilistic flashover times for different wooden lining materials in Case B

				Percentage flashed-over	
	Minimum	5th percentile	50th percentile	900 s	1800 s
Plywood 4 mm (base case)	46 s	65 s	207 s	90%	94%
Plywood FR	31 s	59 s	227 s	89%	96%
MDF 18 mm	53 s	68 s	225 s	88%	94%

6.5 Varying the probability of fuel items to be located against a wall

As discussed in Section 4.4.8, values for the probability of fuel items to be located against a wall are difficult to justify and are set to 0.5 in the base case. This section investigates the effect on time to flashover when this value is changed to 0.2 and 0.8. Base case inputs are used for the FLED (normal distribution with a mean value of 300 MJ/m^2) and the lining materials (plasterboard and plywood). Only Case B (walls and ceiling lined with wooden materials) is analysed.

From Figure 6-9 and Table 6-6 it can be seen that the differences in the flashover times for the different values are just slightly higher than or within the degrees of precision discussed in Section 4.7 and are therefore insignificant.

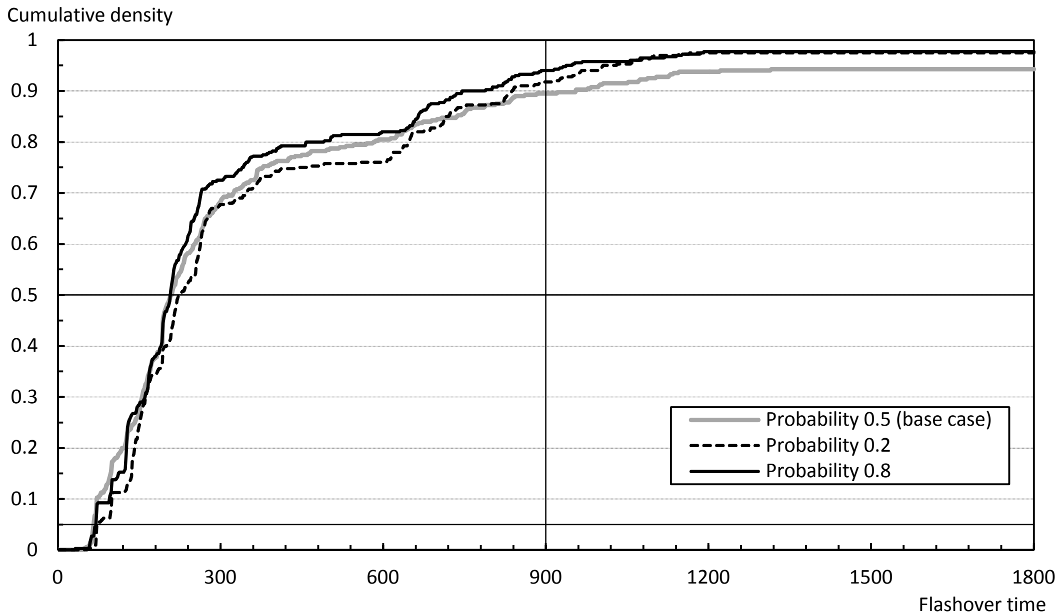


Figure 6-9 Flashover time cumulative densities for different probabilities of items to be located against a wall in Case B

Table 6-6 Probabilistic flashover times for different probabilities of items to be located against a wall in Case B

				Percentage flashed-over	
	Minimum	5th percentile	50th percentile	900 s	1800 s
Probability 0.5 (base case)	46 s	65 s	207 s	90%	94%
Probability 0.2	55 s	70 s	222 s	92%	98%
Probability 0.8	30 s	70 s	206 s	94%	98%

6.6 Comparison to ISO 9705 room-corner tests

Table 6-7 compares the times to flashover observed in ISO 9705 room-corner tests with the relevant probabilistic times to flashover from this study. The data of the ISO 9705 room-corner tests are taken from Wade [23] with flashover considered to occur when the HRR reaches 1000 kW. The probabilistic flashover times refer to the base cases described in Sections 6.2 (plywood) and 6.4 (plywood FR) of this study.

The difference in time to flashover as a representative risk parameter becomes clearly obvious when comparing the results from the standardized hazard analysis test procedure (ISO 9705 room-corner test) with the probabilistic results from a risk analysis which considers uncertainties, i.e. uncertainties in the fuel load configuration in the present study. For example, no flashover occurs in the ISO 9705 test when all linings are non-combustible, since there is no fuel load in the compartment (except of the corner burner). If wooden linings are involved, flashover occurs after approximately 2 minutes. If realistic fuel load arrangements are considered, flashover occurs in any case. The lining material has an influence, as can be seen from the probabilistic flashover times in Table 6-7. However the difference between combustible and non-combustible linings is in the range of one or several minutes if looking at the 5th and 50th percentiles respectively, rather than "infinite" in the ISO 9705 configuration. Using fire retardant plywood instead of non-fire retardant results in no significant difference.

Table 6-7 Experimental times to flashover in ISO 9705 room-corner tests and probabilistic times to flashover from this study

	ISO 9705 room-corner tests [23]	Probabilistic flashover times	
		5th percentile	50th percentile
Case A (all linings plasterboard)	no flashover	119 s	375 s
Case B (walls and ceiling lined with wooden material)			
Plywood	ca. 120 s	65 s	207 s
Plywood FR	ca. 260 s	59 s	227 s
Case C (walls only lined with wooden material)			
Plywood	ca. 120 s	95 s	259 s
Plywood FR	ca. 320 s	no data	no data

7 Conclusions

Two objectives were stated in Section 1.10 for this work: firstly to conduct a quantitative, comparative risk analysis of the fire risk associated with wooden lining materials using B-RISK, and secondly to comment on the functionality of B-RISK for this purpose and give suggestions for improvement to the developers of B-RISK. Recommendations regarding the latter objective are given in the next chapter alongside recommendations for future research in general. This chapter summarizes the findings regarding the first objective.

A risk model has been set up using B-RISK. The scope of the analysis has been confined to the fire growth stage and the room of fire origin. Occupants' response and detection and suppression systems have been excluded from the scope of the analysis. The time to flashover has been defined as a parameter representing the fire risk associated with wooden linings in the given context. Relevant uncertainties have been identified, in particular uncertainties in the arrangement of movable fuel loads.

It has been demonstrated that B-RISK is able to model fire growth on linings similar to BRANZFIRE if the walls and ceiling or the walls only are lined with wooden material, but not if the ceiling only is lined with wooden materials. It has also been demonstrated that B-RISK is able to model fire spread from movable fuel items to wooden lining materials. A comparison with literature data has shown that the differences in flashover times are similar when predicted with B-RISK and observed from full scale experiments. From these findings it is concluded that B-RISK can be used as a tool for comparing flashover times in compartments with wooden and non-combustible linings considering uncertainties in the fuel load configuration (for the cases when the walls and ceiling or the walls only are lined with wooden material).

Multiple iterations have been performed with the risk model, considering varying fuel load arrangements and input values sampled from distributions (Monte-Carlo simulation). From the resulting probabilistic times to flashover the following is concluded:

- If compared with a compartment with non-combustible linings, flashover occurs approximately 30 seconds earlier if the walls are lined with wooden materials and another 30 seconds earlier if the walls and ceiling are lined with combustible material. These numbers refer to 5th percentile values, i.e. 5% of the fires have flashed-over and 95% have not flashed-over, when considering uncertainties in the fuel load configuration.
- Taking the median time to flashover in a room with non-combustible linings as a reference value, flashover occurs approximately 2 minutes earlier if the walls are lined with wooden material, and another minute earlier if the walls and ceiling are lined with wooden material.

- If wooden linings are involved, almost all fires (≥ 94%) lead to flashover, regardless whether linings are applied on walls and ceiling or on walls only. If all linings are non-combustible, flashover occurs in 86% of the fires. After 900 s, in 90% of the iterations flashover has occurred if wooden linings are involved, and in 77% of the iterations if all linings are non-combustible.
- Changes in the fuel load energy density (FLED) do not have any influence on the 5th percentiles of flashover times, and on the median values only when the FLED is comparatively low (100–200 MJ/m^2).
- With lower FLEDs less flashovers occur, particularly when all linings are non-combustible.
- Changing the wooden lining material (e.g. from non-fire retardant plywood to fire retardant plywood) has no effect on the probabilistic flashover times for the investigated materials. Other materials may have a stronger influence on the probabilistic flashover times.

These conclusions are valid for the configuration which is described in this work, in particular:
- ISO 9705 room-corner compartment geometry.
- FLED distribution typical for hotel rooms.
- Randomly chosen first item to be ignited.

A comparison of the probabilistic flashover times with the times to flashover in the ISO 9705 room-corner test clearly shows the differences between the results from the standardized hazard analysis test (ISO 9705) and from the present risk analysis which considers uncertainties in the fuel load configuration. As an example, no flashover occurs in ISO 9705 room-corner tests when all linings are non-combustible, whereas in 86% of the iterations of the present risk analysis flashover occurs, due to the influence of the movable fuel loads.

8 Recommendations

8.1 Introduction

Recommendations are given in this chapter regarding the further development of B-RISK, regarding further research into the fire risk connected with wooden room linings and regarding reviews of prescriptive fire safety code requirements. The recommendations regarding the further development of B-RISK are divided into recommendations on conceptual and detail levels.

8.2 Further development of B-RISK

8.2.1 Conceptual level

The following recommendations are given for the further development of B-RISK based on the experiences and findings in this work:

- As discussed in Section 4.4.4, the HRR of fuel items is one of the major inputs in B-RISK models. However, there is no useful information available on how to model HRRs for secondary ignited items. It is also challenging to account realistically for compartment enhanced burning if HRRs for single items are used. Furthermore, it is relatively time-consuming to define several fuel items with all relevant properties in order to represent a design fire. In fire engineering, these aspects are generally accounted for in a simplified way by using t-squared fire growth curves (Spearpoint [3], Buchanan [6], and International Fire Engineering Guidelines [66]). It would be useful for B-RISK as a design tool, if t-squared fire growths could be used by the designer (with distributions on the growth constant) as an alternative to the HRR from single fuel items.
- It would be useful if dependencies between input distributions could be defined, e.g. between interior and exterior temperatures or exterior temperature and relative humidity.
- The DFG is a useful tool for the consideration of uncertainties in fuel load configurations. In order to better represent real fuel load configurations, the following suggestions might be considered:
    - Give the option to assign “compulsory” items on the fuel items list, which have to be located in the room first in every iteration, and then the DFG would “fill” the room up with randomly chosen items until the specified FLED is reached.
    - Give the option to define an order for the DFG to follow by choosing items from the fuel items list (instead of random choice).
    - Give the option to assign ignition probabilities for each item (instead of random ignition mode, in which every item has equal probability to be ignited).
    - Give the option to define whether a length or width of an item touches the wall.

- As shown in Section 3.2, B-RISK under-predicts in comparison to BRANZFIRE the lining fire growth if the ceiling only is lined with wooden material. Further investigation into this issue would be useful in order to make the fire growth sub-model entirely compatible with B-RISK.

8.2.2 Detail level

The following recommendations are given for the further development of B-RISK based on the experiences and findings in this work:

- Give the option to assign distributions for more parameters, such as heat of gasification and mass loss per unit area (for burning rate enhancement calculation) and radiant loss fraction.
- Additional distribution types would be useful – e.g. the beta general distribution, which is more appropriate for values with upper and lower bounds (rather than “cut” normal distributions).
- Give the option to stop iterations with criteria other than flashover, such as a certain FED or upper layer height.
- In current versions, the DFG can populate a room up to a defined FLED. However this FLED has to be defined under *Options, Post Flashover*, which can be confusing if the user analyses pre-flashover fires with simulations terminated at flashover.
- Graphically distinguish interface fields in which the user can enter values from those in which indicative values are shown (e.g. values with distributions have to be entered after hitting the *Distribution* button and not simply in the field, even if no distribution is chosen). Alternatively just block such fields. Furthermore, in some cases these fields do not show the values which in fact have been defined under *Distribution*.
- Check units and use them consistently (use “°C” instead of “C”, use either kJ/g or MJ/kg consistently for heat of combustion values, etc.).
- Bring “Tab” navigation in input interfaces into a sensible order.
- Debug the vent clearance definition (value is reset to 1.0 m after the *Populate Room* interface is used).

8.3 Further research

From the present study, the following topics are identified where further research is needed or suggested either for the further development of B-RISK or for the understanding of the fire risk associated with wooden room linings:

- As discussed in Section 4.4.4, the currently available knowledge it is not adequate in order to model compartment HRRs which are “correct” in their quantitative magnitude based on multiple item fire spread. Research into the HRR of secondary ignited items is crucial therefore for quantitative, non-comparative risk assessment.

- As discussed in Section 1.8, the ability to model fire growth on linings in a way that is applicable for engineering purposes is confined to particular configurations (ISO 9705 compartment). Research into this topic is needed in order to provide engineers with models to predict fire spread on (wooden) linings for performance-based design of a broader range of configurations – e.g. linings in large compartments or on exterior facades.
- Regarding the assessment of the risk connected with wooden lining materials, the present study could be extended in both directions on the timeline (referring to Table 1-2), in order to cover all relevant uncertainties influencing the fire risk:
    - Include probabilities of ignition and which items are ignited first (consider the work of Robbins and Wade [71]).
    - Include occupant behaviour and relevant effects of alarm systems.
    - Include post-flashover fire stages, i.e. the effects on fire development in directly or indirectly connected rooms (e.g. exitways) or the effects on structural resistance.
- The effects of sprinklers and sprinkler reliability could be integrated into the presented model, in order to calculate relevant probabilistic times to flashover (consider the work of Frank et al. [63]).
- The presented probabilistic times to flashover could be used as an input parameter for analysing of the accepted level of risk regarding the early fire hazard of lining materials. Consider in this regard the β reliability index method, outlined by Yung [72]. Confronting the probabilistic flashover time to a relevant performance requirement, the "safe and unsafe regions" could be calculated. If this is done with configurations which are currently specified by prescriptive fire safety requirements ("deemed-to-satisfy solutions"), the acceptable level of risk would result. Other risk parameters than the time to flashover might be more appropriate for such analyses, e.g. an FED at a certain room height. The model presented in this study could be used for calculating such values.

8.4 Reviews of prescriptive fire safety code requirements

The findings of this work can provide a useful contribution when discussing and evaluating prescriptive fire safety code requirements. As previously shown, the main merits of restricting the use of wooden linings would be the following:

- Flashover can be delayed by approximately one minute, if all linings are non-combustible (5th percentile value of the time to flashover).
- After 15 minutes, 8 out of 10 fires would have flashed-over instead of 9 out of 10, if all linings are non-combustible.

Without referring to or deriving quantified data on the accepted level of risk, the author expresses the opinion that this differences do not justify restrictions on the use of wooden linings. The difference in the 5th percentile values of the time to flashover – one minute – becomes insignificant if the uncertainties in the incipient phase are considered (which has not been done in this study for the reasons mentioned in Section 4.4.4). Therefore, the only merit would be a slightly lower percentage of fires flashed-over after several minutes.

In particular, this conclusion applies to regulations which require fire retardant treatments for wooden linings. With the investigated materials, no difference has been found in the fire risk when a fire retardant lining material is used compared to non-fire retardant materials. Even if there was an effect, the maximum improvement which could be achieved would be a reduction of the number of flashovers from roughly 9 out of 10 down to 8 out of 10.

It is emphasized that these statements apply to the fire risk connected with wooden lining materials in the pre-flashover fire stages in occupied rooms. Recommendations for further research regarding the post-flashover fire stages are given in Section 8.3.

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Annexes

A1 History of B-RISK development versions

Update versions of B-RISK with development notes from the Beta Software section on www.branzfire.com/frst:

February 23, 2012 - B-RISK (2012.0.9.13178)

time series plots export data to excel function was broken - fixed.

February 14, 2012 - B-RISK (2012.0.8.17931)

changed format of sprinkler.xml file. If you have trouble delete and regenerate your sprinklers.xml file.

sprinkler distributions interface changed to match that for items.

percentile time series plots fixed for UT, FED, LT.

adding new room - fixed problem where dimensions of existing room not saved.

January 31, 2012 - B-RISK (2012.0.7.14936)

fixed display of item layout recall (was broken).

added export data to excel for upper percentile plots.

January 25, 2012 - B-RISK (2012.0.6.22950)

Individual item distributions functional for heat of combustion, soot yield, co2 yield, and latent heat of gasification,

misc debugging.

January 24, 2012 - B-RISK (2012.0.5.35289)

added additional outputs to upper percentile time series plots.

debugging user label display option for room contents layout.

rewrote code to delete existing input/output files prior to running simulation to be much quicker.

added item properties for mass loss per unit area to optionally replace the global value given under the combustion parameters screen. The mass loss per unit area is given in the form m = Aq + B where A and B are constants defined under the item properties and q is the external heat flux impinging on the item (ie. target radiation from hot layer and room surfaces impinging on the top surface of the item). If A and B are left as zero in the item properties, the existing global mass loss per unit area parameter is used.

added latent heat of gasification as item property, with option to define it with a distribution. ***NOTE - DISTRIBUTIONS NOT YET WORKING***

January 20, 2012 - B-RISK (2012.0.4.30421)

Added user label as new item property. This can be displayed on the layout plan in the room population screen to provide more user friendly description of each item.

Added new time series outputs for an upper percentile curve for either HRR or upper layer temperature.

January 17, 2012 - B-RISK (2012.0.3.24251)

Room population module - debugging.

FLED actual - export to excel

Misc debugging.

January 12, 2012 - B-RISK (2012.0.2.14118)

Room population module - modifed to allow further items to be added following an item that is too large to fit.

Ventfires added to output / excel.

FLED - actual and sampled values included in output.

Export of dumpfile data to excel modified to allow for multiple rooms.

Misc debugging.

January 4, 2012 - B-RISK (2012.0.1.25712)

Added new variable for sprinkler cooling coefficient including distributions input.

Criteria for terminating simulations on flashover only recognised the upper layer temperature and not flux criteria. Fixed.

December 23, 2011 - B-RISK (2011.0.28.17982)

Add Items fixed.

December 21, 2011 - B-RISK (2011.0.27.17903)

*** Add Items command not working, add items by editing the items.xml file directly until fixed ***

Debugging of excel export functions. Anomaly in ordering of iterations between excel and output files corrected. Option to save all output as csv file.

December 18, 2011 - B-RISK (2011.0.26.30396)

Errors in flame spread routine corrected.

Right click on log output to copy to clipboard or save to file.

December 17, 2011 - B-RISK (2011.0.25.33529)

December 16, 2011 - B-RISK (2011.0.24.12112)

*** some problems adding, deleting items, wait for next version ***

Distributions for individual item properties for heat of combustion, soot yield and CO2 yield are enabled, using a revised backend for creating distributions.

Format of items.xml file changed from 2011.0.23 - upgrade to new format is done automatically.

December 8, 2011 - B-RISK (2011.0.23.40965)

Debugging to fix secondary item ignition.

Added new sprinkler capability including probability of suppression, and discrete distribution for number of sprinklers required for suppression. Notes to follow on this.

The riskdata folder requires a 'distributions.xml' file to hold information about input variables with statistical distributions. If you are loading up an old model that does not have this file, then copy the one in the basemodel_default folder to your riskdata project folder.

December 6, 2011 - B-RISK (2011.0.22.18360)

secondary item ignition is broken

Flame spread - debugging.

Partial rework of distributions interface in progress. The riskdata folder now requires a 'distributions.xml' file to hold information about input variables with statistical distributions. Eventually those variables will be removed from the basemodel_*.xml file.

November 25, 2011 - B-RISK (2011.0.21.23374)

secondary item ignition is broken

Wall and Ceiling flame spread routines now integrated with DFG. Individual items can ignite wall and/or ceiling linings. Items can be at any location in the room and exposures to room surfaces will be assessed as well as exposure to other items.

DOWNLOAD - download notes on flame spread.

November 15, 2011 - B-RISK (2011.0.20.40659)

Burning rate enhancement algorithm improved to work with DFG.

DOWNLOAD - download notes on enhanced burning option.

Ceiling jet / sprinkler routines now use radiant loss fraction for the first item ignited rather than the global value.

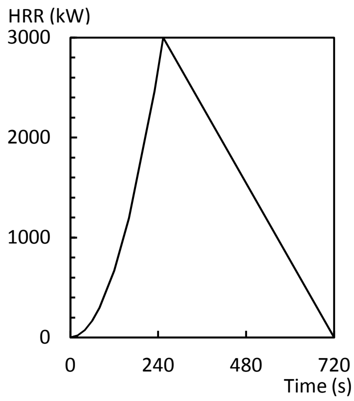
November 8, 2011 - B-RISK (2011.0.19.21863)

Miscellaneous changes to better integrate the flame spread sub-model with the DFG.

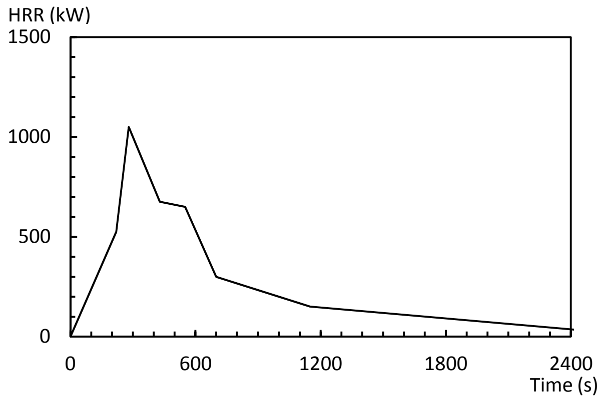
Flame spread graphical outputs added.

A2 Fuel items

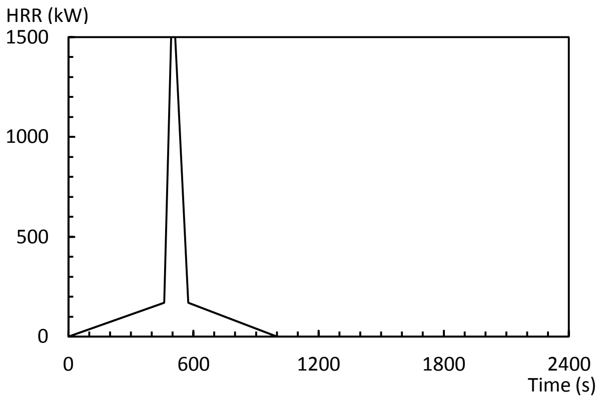
Fuel item 0: Bed for modular hotel room scenario

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	24	[4]
Length (m)	2.0	[45]
Width (m)	1.6	[45]
Height (m)	0.5	[45]
Elevation (m)	0.0	[45]
Mass (kg)	39.9	Calculated from the total energy released (area under HRR curve) and the heat of combustion. The actual weight of the mattresses was according to [4], Table 4, 20.8 kg to 24.9 kg. The additional weight accounts for the contribution of the pallets, which were used in the test but not explicitly considered here.
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index n	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index n	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 20, 19 40, 75 60, 168 80, 298 120, 671 160, 1193 230, 2465 254, 3000 720, 0	Peak HRR: [59] summarises HRRs of up to 2.7 MW for mattresses with a weight of up to 19 kg (no room effects). A peak HRR of 3 MW is set therefore to account for the additional weight of the tested mattresses (20.8 kg to 24.9 kg) and the contribution of the pallets under the mattress. Time of peak HRR: 254 s is the time necessary to reach 3 MW in a fast αt^2-fire (α = 0.047). Total duration: [45] reports a free burning test of a mattress. 10 min. after ignition the burning intensity decreased significantly, and after 18 min. the mattress was consumed completely. To account for the room effects, a total duration of 720 s is set.
HRR curve		
Fuel load energy (MJ)	958	Calculated from HRR curve

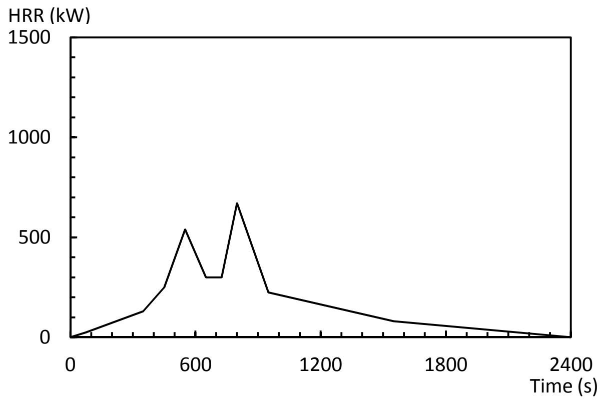
Fuel item 1: Wood frame loveseat

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	15.1	[68], Test 57
Length (m)	1.4	[68], Test 57
Width (m)	0.8	[68], Test 57
Height (m)	0.8	[68], Test 57
Elevation (m)	0.0	Model assumption
Mass (kg)	40.4	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 220, 525 280, 1050 430, 675 550, 650 700, 300 1150, 150 2800, 0	[68], Test 57. Free burning HRR (furniture calorimeter test). 500 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	610	Calculated from HRR curve

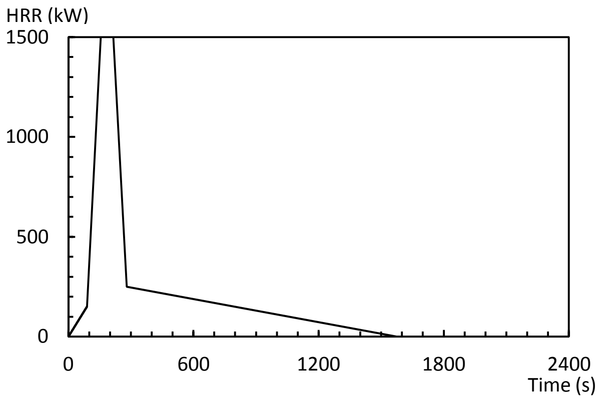
Fuel item 2: PU foam spring-core mattress

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	26	[66], Section 3.3.2, PU foam
Length (m)	1.9	[68], Test 74
Width (m)	1.3	[68], Test 74
Height (m)	0.2	[68], Test 74
Elevation (m)	0.3	Model assumption
Mass (kg)	7.2	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 460, 170 500, 1770 575, 170 1000, 0	[68], Test 74. Free burning HRR (furniture calorimeter test). 225 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	187	Calculated from HRR curve

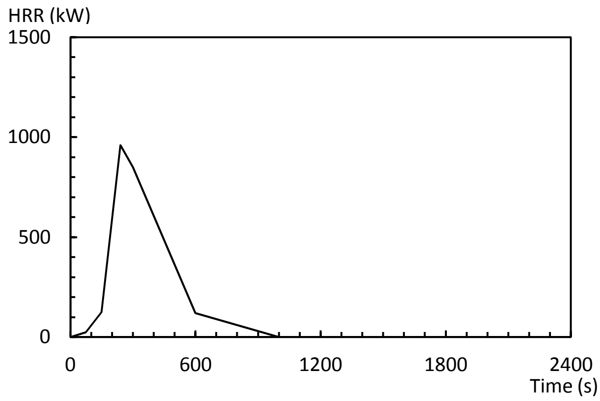
Fuel item 3: PU/cotton mattress with boxspring

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	22	Average for PU foam and wood from [66], Section 3.3.2
Length (m)	1.9	[68], Test 67
Width (m)	1.3	[68], Test 67
Height (m)	0.3	[68], Test 67
Elevation (m)	0.2	Model assumption
Mass (kg)	17.0	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index n	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index n	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 75, 25 350, 130 450, 250 550, 540 650, 300 725, 300 800, 670 950, 225 1550, 80 2400, 0	[68], Test 67. Free burning HRR (furniture calorimeter test). 150 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	374	Calculated from HRR curve

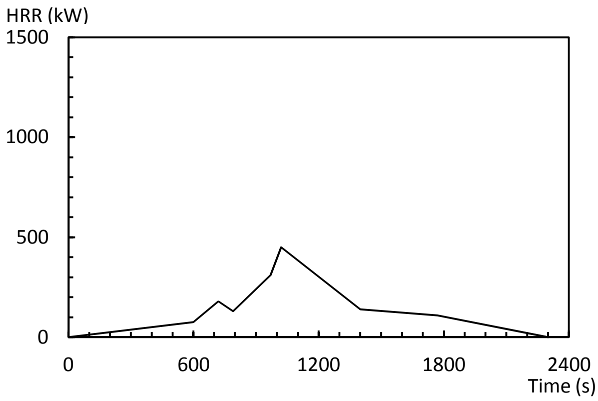
Fuel item 10: "California foam" easy chair

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	18.1	[68], Test 45
Length (m)	0.8	[68], Test 45
Width (m)	0.8	[68], Test 45
Height (m)	0.8	[68], Test 45
Elevation (m)	0.0	Model assumption
Mass (kg)	21.4	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit ($s(kW/m^2)^n$)	471	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit ($s(kW/m^2)^n$)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 90, 150 185, 2100 280, 250 1575, 0	[68], Test 45. Free burning HRR (furniture calorimeter test). 75 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	387	Calculated from HRR curve

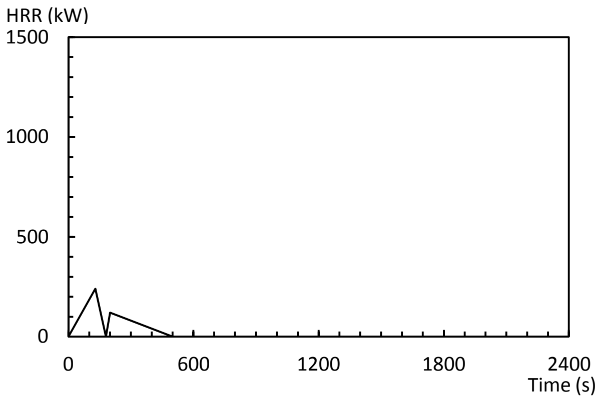
Fuel item 11: PS/plywood/PU easy chair

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	33	[68], Test 48
Length (m)	0.8	[68], Test 48
Width (m)	0.8	[68], Test 48
Height (m)	0.8	[68], Test 48
Elevation (m)	0.0	Model assumption
Mass (kg)	8.5	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 75, 25 150, 125 240, 960 300, 850 600, 120 1000, 0	[68], Test 48. Free burning HRR (furniture calorimeter test).
HRR curve		
Fuel load energy (MJ)	280	Calculated from HRR curve

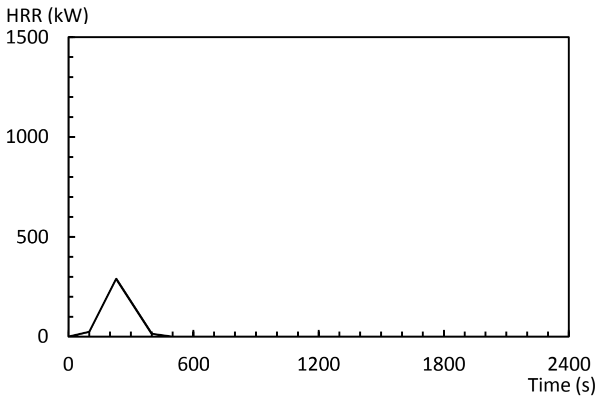
Fuel item 12: Polyester/wood/PU easy chair

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	21	[68], Test 64
Length (m)	0.8	[68], Test 64
Width (m)	0.8	[68], Test 64
Height (m)	0.7	[68], Test 64
Elevation (m)	0.0	Model assumption
Mass (kg)	14	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 600, 75 720, 180 790, 130 970, 310 1020, 450 1400, 140 1770, 110 2300, 0	[68], Test 64. Free burning HRR (furniture calorimeter test). 300 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	295	Calculated from HRR curve

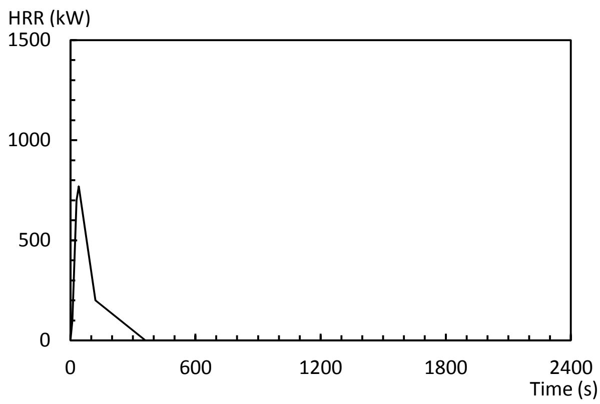
Fuel item 20: Metal frame chair with adjustable back

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	21.8	[68], Test 47
Length (m)	0.5	[68], Test 47
Width (m)	0.8	[68], Test 47
Height (m)	0.6	[68], Test 47
Elevation (m)	0.4	Model assumption
Mass (kg)	2.0	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index n	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index n	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 130, 240 180, 0 200, 120 500, 0	[68], Test 47. Free burning HRR (furniture calorimeter test).
HRR curve		
Fuel load energy (MJ)	41	Calculated from HRR curve

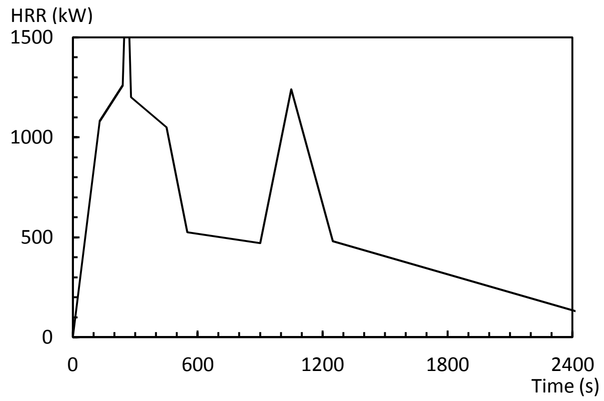
Fuel item 21: Metal frame chair with PU cushions

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	21.4	[68], Test 53
Length (m)	0.5	[68], Test 53
Width (m)	0.5	[68], Test 53
Height (m)	0.5	[68], Test 53
Elevation (m)	0.5	Model assumption
Mass (kg)	2.2	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit (s(kW/m^2)^n)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 100, 25 230, 290 400, 15 500, 0	[68], Test 53. Free burning HRR (furniture calorimeter test).
HRR curve		
Fuel load energy (MJ)	48	Calculated from HRR curve

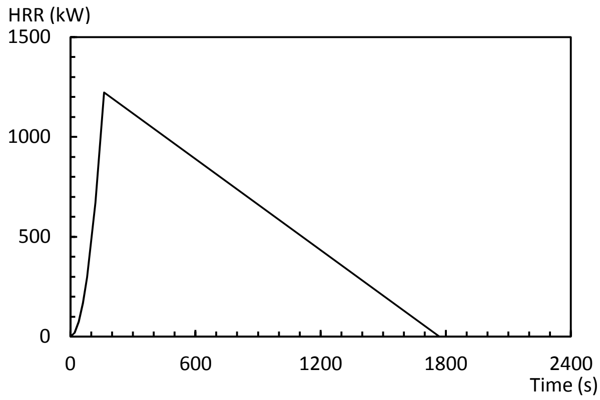
Fuel item 30: Metal wardrobe

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	14.8	[68], Test 15
Length (m)	1.2	[68], Test 15
Width (m)	0.5	[68], Test 15
Height (m)	1.6	[68], Test 15
Elevation (m)	0.0	Model assumption
Mass (kg)	5.3	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit ($s(kW/m^2)^n$)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit ($s(kW/m^2)^n$)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 10, 100 30, 700 40, 770 120, 200 360, 0	[68], Test 15. Free burning HRR (furniture calorimeter test). 20 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	79	Calculated from HRR curve

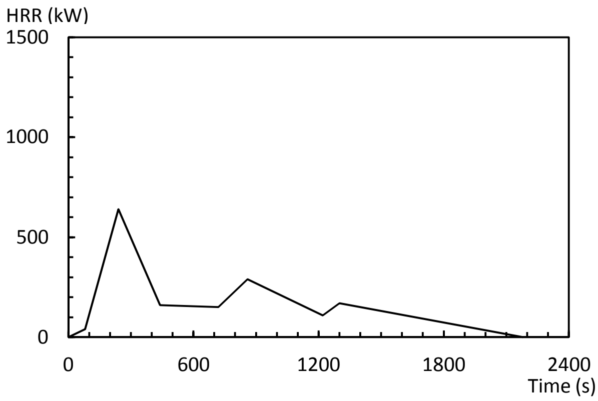
Fuel item 31: Particleboard wardrobe

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	17.5	[68], Test 61
Length (m)	1.2	[68], Test 61
Width (m)	0.4	[68], Test 61
Height (m)	1.8	[68], Test 61
Elevation (m)	0.0	Model assumption
Mass (kg)	79.5	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	5370	[60], Table 6, chipboard
FTP index *n*	1.49	[60], Table 6, chipboard
Critical flux (kW/m^2)	6.4	[60], Table 6, chipboard
Auto ignition		
FTP limit (s(kW/m^2)^n)	4751	Derived according to Table 4-5
FTP index *n*	1.49	
Critical flux (kW/m^2)	15.4	
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 130, 1080 240, 1260 260, 1950 280, 1200 450, 1050 550, 525 900, 470 1050, 1240 1250, 480 2850, 0	[68], Test 61. Free burning HRR (furniture calorimeter test).
HRR curve		
Fuel load energy (MJ)	1391	Calculated from HRR curve

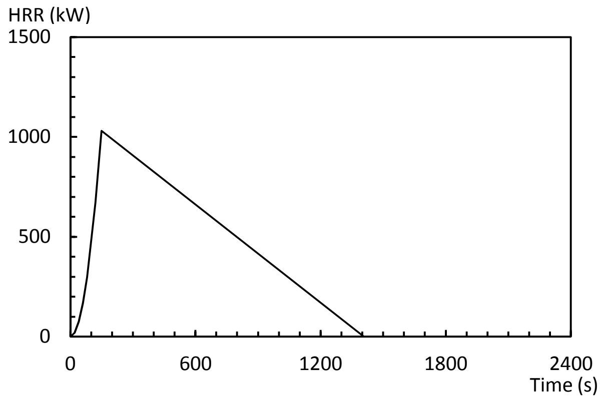
Fuel item 40: Table constructed out of wood pallets for modular hotel room scenario

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	17.5	[4], Table 4
Length (m)	0.8	[45]
Width (m)	1.2	[45]
Height (m)	1.0	[45]
Elevation (m)	0.0	[45]
Mass (kg)	60	[45]
Piloted ignition		
FTP limit ($s(kW/m^2)^n$)	5130	[60], Table 6, softwood
FTP index *n*	1.53	[60], Table 6, softwood
Critical flux (kW/m^2)	13.7	[60], Table 6, softwood
Auto ignition		
FTP limit ($s(kW/m^2)^n$)	3784	Derived according to Table 4-5
FTP index *n*	1.53	
Critical flux (kW/m^2)	32.9	
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 20, 19 40, 75 60, 168 80, 298 120, 671 162, 1223 1770, 0	Peak HRR: According to the correlation in [59] for pallets, assuming a stack of 3 pallets with a dimension of 0.42 m × 1.0 m × 1.2 m [45]. Time to peak HRR: 162 s is the time necessary to reach 1223 kW in a fast αt^2-fire (α = 0.047). Total duration: set in a way that the energy released is equal to the product of the mass and heat of combustion.
HRR curve		
Fuel load energy (MJ)	1050	Calculated from mass and heat of combustion

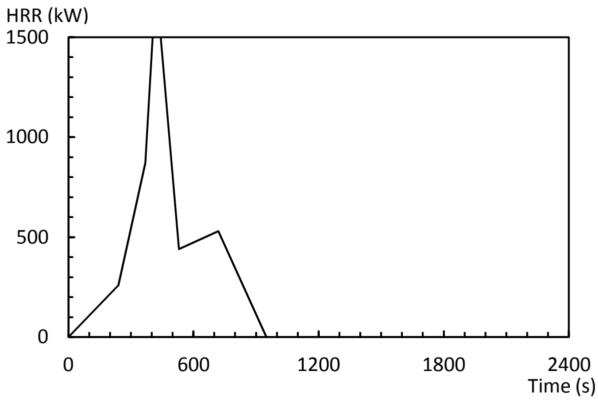
Fuel item 41: Wooden desk

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	18	[66], Section 3.3.2, wood
Length (m)	0.9	Model assumption
Width (m)	0.5	Model assumption
Height (m)	0.7	Model assumption
Elevation (m)	0.0	Model assumption
Mass (kg)	20	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	5130	[60], Table 6, softwood
FTP index *n*	1.53	[60], Table 6, softwood
Critical flux (kW/m^2)	13.7	[60], Table 6, softwood
Auto ignition		
FTP limit (s(kW/m^2)^n)	3784	Derived according to Table 4-5
FTP index *n*	1.53	
Critical flux (kW/m^2)	32.9	
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 80, 40 240, 640 440, 160 850, 150 860, 290 1220, 110 1300, 170 2180, 0	[59], Figure 3-1.36. No room effects mentioned. 120 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	360	Calculated from HRR curve

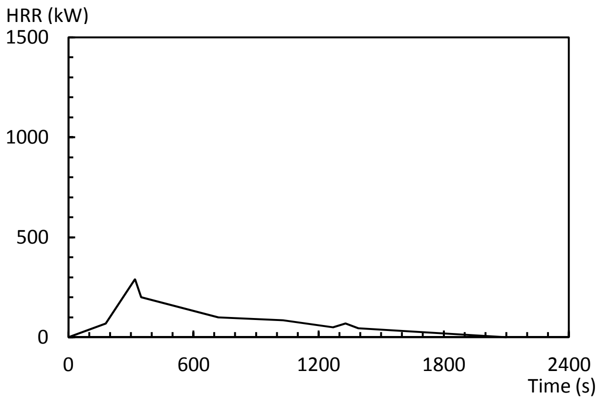
Fuel item 50: Dresser constructed out of wood pallets for modular hotel room scenario

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	17.5	[4], Table 4
Length (m)	0.3	[45]
Width (m)	0.8	[45]
Height (m)	1.2	[45]
Elevation (m)	0.0	[45]
Mass (kg)	40	[45]
Piloted ignition		
FTP limit (s(kW/m^2)^n)	5130	[60], Table 6, softwood
FTP index *n*	1.53	[60], Table 6, softwood
Critical flux (kW/m^2)	13.7	[60], Table 6, softwood
Auto ignition		
FTP limit (s(kW/m^2)^n)	3784	Derived according to Table 4-5
FTP index *n*	1.53	
Critical flux (kW/m^2)	32.9	
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 20, 19 40, 75 60, 168 80, 298 120, 671 149, 1030 1407, 0	Peak HRR: According to the correlation in [59] for pallets, assuming a stack of 2 pallets with a dimension of 0.28 m × 1.0 m × 1.2 m [45]. Time to peak HRR: 149 s is the time necessary to reach 1030 kW in a fast αt^2-fire (α = 0.047). Total duration: set in a way that the energy released is equal to the product of the mass and heat of combustion.
HRR curve		
Fuel load energy (MJ)	700	Calculated from HRR curve

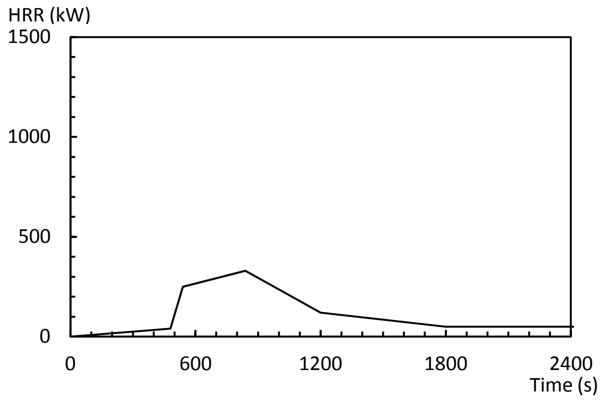
Fuel item 51: Wooden dresser

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	18	[66], Section 3.3.2, wood
Length (m)	0.8	Model assumption
Width (m)	0.4	Model assumption
Height (m)	1.0	Model assumption
Elevation (m)	0.0	Model assumption
Mass (kg)	24.1	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit ($s(kW/m^2)^n$)	6164	[60], Table 6, plywood
FTP index *n*	1.51	[60], Table 6, plywood
Critical flux (kW/m^2)	10.6	[60], Table 6, plywood
Auto ignition		
FTP limit ($s(kW/m^2)^n$)	4946	Derived according to Table 4-5
FTP index *n*	1.51	
Critical flux (kW/m^2)	25.4	
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 240, 260 370, 870 420, 1780 530, 440 720, 530 900, 0	[59], Figure 3-1.38. No room effects mentioned.
HRR curve		
Fuel load energy (MJ)	433	Calculated from HRR curve

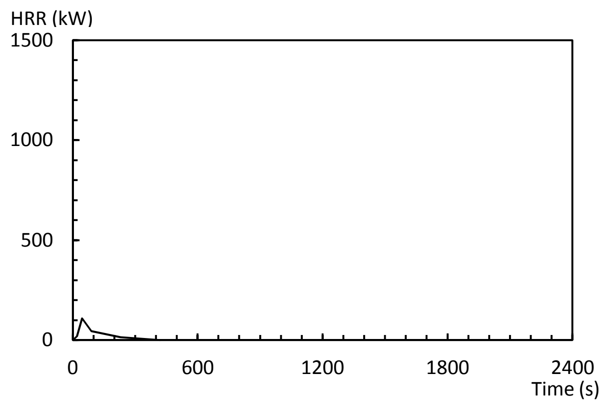
Fuel item 60: European television set

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	30	Value from [66], Section 3.3.2, which is representative for a range of synthetic solids (such as PE, 44 MJ/kg, and PVC, 17 MJ/kg)
Length (m)	0.4	Model assumption
Width (m)	0.5	Model assumption
Height (m)	0.5	Model assumption
Elevation (m)	1.8	Model assumption
Mass (kg)	5.4	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit ($s(kW/m^2)^n$)	2220	[60], Table 6, PE
FTP index *n*	1	[60], Table 6, PE
Critical flux (kW/m^2)	12.5	[60], Table 6, PE
Auto ignition		
FTP limit ($s(kW/m^2)^n$)	1859	Derived according to Table 4-5
FTP index *n*	1	
Critical flux (kW/m^2)	30.0	
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 180, 70 320, 290 350, 200 720, 100 1030, 85 1270, 50 1330, 70 1390, 45 2100, 0	[59], Table 3-1.24, TW3. No room effects mentioned. 350 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	162	Calculated from HRR curve

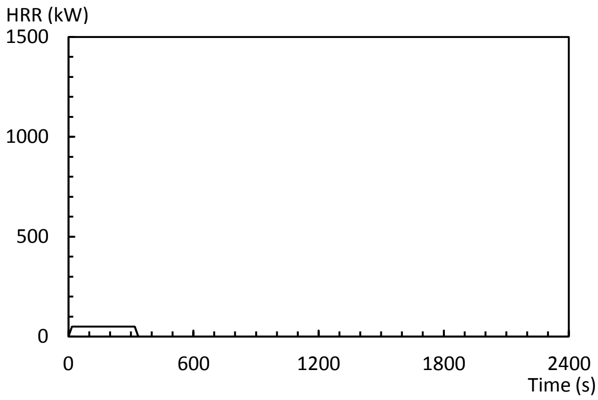
Fuel item 61: European washing machine

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	26.5	Calculated from HRR curve and mass
Length (m)	0.5	Model assumption
Width (m)	0.4	Model assumption
Height (m)	0.4	Model assumption
Elevation (m)	0.2	Model assumption
Mass (kg)	11.8	[59], Table 3-1.32, W1
Piloted ignition		
FTP limit (s(kW/m^2)^n)	8110	[60], Table 6, PP
FTP index *n*	1.5	[60], Table 6, PP
Critical flux (kW/m^2)	6.5	[60], Table 6, PP
Auto ignition		
FTP limit (s(kW/m^2)^n)	7154	Derived according to Table 4-5
FTP index *n*	1.5	
Critical flux (kW/m^2)	15.6	
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 480, 40 540, 250 840, 330 1200, 120 1800, 50 3000, 50 3600, 0	[59], Figure 3-1.106, W1. No room effects mentioned. 600 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	312	Calculated from HRR curve; in good agreement with value cited in [59], Table 3-1.32, W1

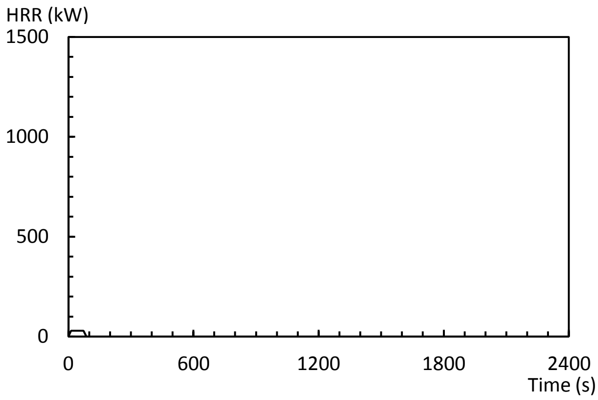
Fuel item 70: Cotton/polyester curtain 64% pleated

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	25.8	Weighted average of polyester (60%) and cotton (40%) from [66], Section 3.3.2
Length (m)	0.1	1.4 m × 36% [69]
Width (m)	0.5	Model assumption
Height (m)	1.8	[69]
Elevation (m)	0.1	Model assumption
Mass (kg)	0.43	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit ($s(kW/m^2)^n$)	481	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	9.5	As derived in [52] for foam-padding-fabric
Auto ignition		
FTP limit ($s(kW/m^2)^n$)	427	As derived in [52] for foam-padding-fabric
FTP index *n*	1	As derived in [52] for foam-padding-fabric
Critical flux (kW/m^2)	22.0	As derived in [52] for foam-padding-fabric
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 20, 20 45, 110 90, 45 230, 15 420, 0	[69], Figure 8, 40% cotton. Includes room effects (ISO 9705). 30 s incipient stage ignored.
HRR curve		
Fuel load energy (MJ)	11	Calculated from HRR curve

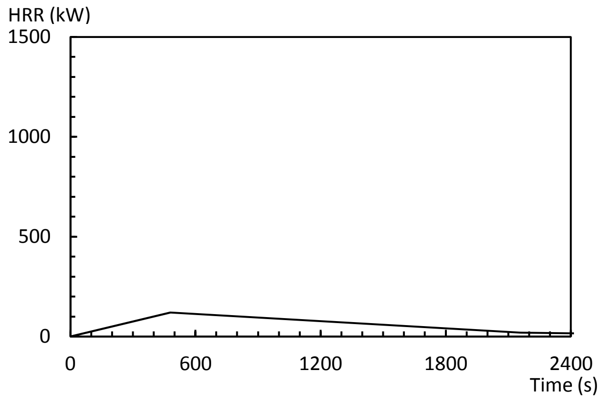
Fuel item 71: Wastebasket Yamada

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	31	Average for PE and wood from [66], Section 3.3.2
Length (m)	0.2	Model assumption
Width (m)	0.2	Model assumption
Height (m)	0.3	Model assumption
Elevation (m)	0	Model assumption
Mass (kg)	0.51	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	2220	[60], Table 6, PE
FTP index *n*	1	[60], Table 6, PE
Critical flux (kW/m^2)	12.5	[60], Table 6, PE
Auto ignition		
FTP limit (s(kW/m^2)^n)	1859	Derived according to Table 4-5
FTP index *n*	1	
Critical flux (kW/m^2)	30.0	
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 18, 50 318, 50 336, 0	[59], trash bags and containers, Yamada citation. No room effects mentioned.
HRR curve		
Fuel load energy (MJ)	16	Calculated from HRR curve

Fuel item 72: Wastebasket Mehaffey

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	30.5	Average for PP and wood from [66], Section 3.3.2
Length (m)	0.2	Model assumption
Width (m)	0.2	Model assumption
Height (m)	0.3	Model assumption
Elevation (m)	0	Model assumption
Mass (kg)	0.07	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	8110	[60], Table 6, PP
FTP index *n*	1.5	[60], Table 6, PP
Critical flux (kW/m^2)	6.5	[60], Table 6, PP
Auto ignition		
FTP limit (s(kW/m^2)^n)	7154	Derived according to Table 4-5
FTP index *n*	1.5	
Critical flux (kW/m^2)	15.6	
Radiant loss fraction	0.3	As recommended by [62] for cases "without specific knowledge"
Time (s), HRR (kW)	0, 0 13, 30 73, 30 86, 0	[59], trash bags and containers, Mehaffey citation. No room effects mentioned.
HRR curve		
Fuel load energy (MJ)	2	Calculated from HRR curve

Fuel item 73: Hard suitcase

Characteristics		Source/derivation
Heat of combustion (MJ/kg)	30.5	Average for PP and cotton from [66], Section 3.3.2
Length (m)	0.6	Model assumption
Width (m)	0.4	Model assumption
Height (m)	0.2	Model assumption
Elevation (m)	0.4	Model assumption
Mass (kg)	5.3	Calculated from HRR curve and heat of combustion
Piloted ignition		
FTP limit (s(kW/m^2)^n)	8110	[60], Table 6, PP
FTP index *n*	1.5	[60], Table 6, PP
Critical flux (kW/m^2)	6.5	[60], Table 6, PP
Auto ignition		
FTP limit (s(kW/m^2)^n)	7154	Derived according to Table 4-5
FTP index *n*	1.5	
Critical flux (kW/m^2)	15.6	
Radiant loss fraction	0.3	As recommended by [62] for cases “without specific knowledge”
Time (s), HRR (kW)	0, 0 480, 120 2160, 20 3600, 0	[59], Figure 3-1.55. No room effects mentioned.
HRR curve		
Fuel load energy (MJ)	161	Calculated from HRR curve

A3 Model inputs and log-files for comparison with experiment

Modular hotel room with wooden linings – inputs

DESCRIPTION OF ROOM	
Room length (m)	6.3
Room width (m)	2.9
Room height (m)	2.4
Wall surface: MDF 18 mm	
Density (kg/m^3)	720
Conductivity (W/mK)	0.15
Emissivity	0.88
Thickness (mm)	18
Wall substrate: Polystyrene FR	
Density (kg/m^3)	37
Conductivity (W/mK)	0.03
Thickness (mm)	100
Ceiling surface: MDF 18 mm	
Density (kg/m^3)	720
Conductivity (W/mK)	0.15
Emissivity	0.88
Thickness (mm)	18
Ceiling substrate: Polystyrene FR	
Density (kg/m^3)	37
Conductivity (W/mK)	0.03
Thickness (mm)	100
Floor surface: MDF 18 mm	
Density (kg/m^3)	720
Conductivity (W/mK)	0.15
Emissivity	0.88
Thickness (mm)	18
Floor substrate: Polystyrene FR	
Density (kg/m^3)	37
Conductivity (W/mK)	0.03
Thickness (mm)	100

FLAME SPREAD MODE	on
Flame length power	1.00
Flame area constant	0.0065
Ignition correlations	FTP
Cone data: KaisMDF.txt	
AMBIENT CONDITIONS	
Interior temperature	
Triangular distribution	
Most likely (°C)	22
Minimum (°C)	15
Maximum (°C)	30
Exterior temperature	
Normal distribution	
Mean (°C)	8
Variance (°C)	100
Lower bound (°C)	-15
Upper bound (°C)	45
Relative humidity	
Triangular distribution	
Most likely (°C)	50
Minimum (°C)	20
Maximum (°C)	75
WALL VENT	
Vent width (m)	1.6
Vent height (m)	1.4
Vent sill height (m)	0.75
ENHANCED BURNING RATE	Off
PLUME MODEL	McCaffrey

Remarks:

Room geometry according to [4], [45]

Surfaces: in test OSB (walls) and multi-layer solid wood panel (floor and ceiling); however there is no cone data readily available for these materials. Therefore MDF 18 mm (Cone data “KaisMDF.txt”, from Li [57]) is used as a best approximation regarding thermal and ignition properties.

Substrates: in test mineral wool; however there is no data available in BRANZFIRE for mineral wool. Therefore polystyrene FR is used as a best approximation regarding thermal properties.

Ambient conditions as for Zurich, Switzerland

Modular hotel room with wooden linings – log-file

```
Simulation Finished.
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 20
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 19
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 18
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 17
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 16
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 15
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 14
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 13
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 12
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 11
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 10
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 9
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 8
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 7
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 6
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
```

```
Iteration 5
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 4
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 3
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 2
40 sec. Flashover in Room 1.
36 sec. Wall in Room 1 has ignited.
36 sec. Ceiling in Room 1 ignited.
Iteration 1
```

Modular hotel room with non-combustible linings – inputs

DESCRIPTION OF ROOM		FLAME SPREAD MODE	off
Room length (m)	6.3	Flame length power	-
Room width (m)	2.9	Flame area constant	-
Room height (m)	2.4	Ignition correlations	-
Wall surface: Plasterboard		Cone data: --	
Density (kg/m^3)	810		
Conductivity (W/mK)	0.16	AMBIENT CONDITIONS	
Emissivity	0.88	Interior temperature	
Thickness (mm)	15	Triangular distribution	
Wall substrate: Polystyrene FR		Most likely (°C)	22
Density (kg/m^3)	37	Minimum (°C)	15
Conductivity (W/mK)	0.03	Maximum (°C)	30
Thickness (mm)	100	Exterior temperature	
Wall surface: Plasterboard		Normal distribution	
Density (kg/m^3)	810	Mean (°C)	8
Conductivity (W/mK)	0.16	Variance (°C)	100
Emissivity	0.88	Lower bound (°C)	-15
Thickness (mm)	15	Upper bound (°C)	45
Ceiling substrate: Polystyrene FR		Relative humidity	
Density (kg/m^3)	37	Triangular distribution	
Conductivity (W/mK)	0.03	Most likely (°C)	50
Thickness (mm)	100	Minimum (°C)	20
Floor surface: MDF 18 mm		Maximum (°C)	75
Density (kg/m^3)	720		
Conductivity (W/mK)	0.15	WALL VENT	
Emissivity	0.88	Vent width (m)	1.6
Thickness (mm)	18	Vent height (m)	1.4
Floor substrate: Polystyrene FR		Vent sill height (m)	0.75
Density (kg/m^3)	37	ENHANCED BURNING RATE	Off
Conductivity (W/mK)	0.03	PLUME MODEL	McCaffrey
Thickness (mm)	100		

Remarks:

Room geometry according to [4], [45]

Substrates: in test mineral wool; however there is no data available in BRANZFIRE for mineral wool. Therefore polystyrene FR is used as a best approximation regarding thermal properties.

Ambient conditions as for Zurich, Switzerland

Modular hotel room with non-combustible linings – log-file

```
Simulation Finished.
185 sec. Flashover in Room 1.
Iteration 20
186 sec. Flashover in Room 1.
Iteration 19
187 sec. Flashover in Room 1.
Iteration 18
185 sec. Flashover in Room 1.
Iteration 17
185 sec. Flashover in Room 1.
Iteration 16
187 sec. Flashover in Room 1.
Iteration 15
186 sec. Flashover in Room 1.
Iteration 14
186 sec. Flashover in Room 1.
Iteration 13
186 sec. Flashover in Room 1.
Iteration 12
188 sec. Flashover in Room 1.
Iteration 11
187 sec. Flashover in Room 1.
Iteration 10
187 sec. Flashover in Room 1.
Iteration 9
186 sec. Flashover in Room 1.
Iteration 8
187 sec. Flashover in Room 1.
Iteration 7
187 sec. Flashover in Room 1.
Iteration 6
185 sec. Flashover in Room 1.
Iteration 5
186 sec. Flashover in Room 1.
Iteration 4
186 sec. Flashover in Room 1.
Iteration 3
186 sec. Flashover in Room 1.
Iteration 2
186 sec. Flashover in Room 1.
Iteration 1
```

A4 Sample B-RISK input files

Input files for simulation in Section 6.1, Case C

basemodel_6.1_C.xml


```
<?xml version="1.0" encoding="utf-8"?>
<!--Created by BRANZFIRE Version 2012.09-->
<!--Input File B-RISK DESIGN FIRE TOOL (2012.0.9.13178)-->
<simulation>
 <general_settings>
  <version>2012.09</version>
  <file_type>montecarlo</file_type>
  <description> ISO 9705 Full-scale room corner fire test
simulation</description>
  <number_iterations>400</number_iterations>
  <output_interval>1</output_interval>
  <vent_clearance>0.8</vent_clearance>
  <grid_size>0.1</grid_size>
  <base_name>basemodel_6.1_C</base_name>
  <spr_reliability
   distribution=""
   value="0"
   mean="0"
   variance="0"
   lbound="0"
   ubound="0" />
  <spr_num_prob
   sprnum1="0"
   sprnum2="0"
   sprnum3="0"
   sprnum4="0" />
  <temp_interior
   distribution=""
   value="0"
   mean="0"
   variance="0"
   lbound="0"
   ubound="0" />
  <temp_exterior
   distribution=""
   value="0"
   mean="0"
   variance="0"
   lbound="0"
   ubound="0" />
  <rel_humidity
   distribution=""
   value="0"
   mean="0"
   variance="0"
   lbound="0"
   ubound="0" />
  <simulation_duration>1800</simulation_duration>
  <display_interval>10</display_interval>
  <ceiling_nodes>15</ceiling_nodes>
  <wall_nodes>15</wall_nodes>
  <floor_nodes>10</floor_nodes>
  <enhance_burning>False</enhance_burning>
  <job_number />
  <excel_interval>2</excel_interval>
  <time_step>1</time_step>
  <error_control>0.1</error_control>
  <fire_dbase>C:\Users\branzcw\Documents\B-
RISK\dbases\fire.mdb</fire_dbase>
  <mat_dbase>C:\Users\branzcw\Documents\B-
RISK\dbases\thermal.mdb</mat_dbase>
  <ceiling_jet>0</ceiling_jet>
  <vent_logfile>False</vent_logfile>
  <LE_Solver>Gauss-Jordan</LE_Solver>
  <no_wall_flow>False</no_wall_flow>
  <sprink_mode>0</sprink_mode>
  <auto_populate>True</auto_populate>
  <calc_sprdist>False</calc_sprdist>
  <ignite_secitems>True</ignite_secitems>
  <firstitem>0</firstitem>
 </general_settings>
 <rooms
  number_rooms="1">
  <room
   id="1"
   ceilingslope="False">
   <width>2.4</width>
   <length>3.6</length>
   <max_height>2.4</max_height>
   <description />
   <min_height>2.4</min_height>
   <floor_elevation>0</floor_elevation>
   <two_zones>True</two_zones>
   <wall_lining>
    <description>plywood 4 mm</description>
    <thickness>4</thickness>
    <conductivity>0.12</conductivity>
    <specific_heat>1215</specific_heat>
    <density>580</density>
    <emissivity>0.88</emissivity>
    <cone_file>ply104all.txt</cone_file>
    <min_temp_spread>437</min_temp_spread>
    <flame_spread_parameter>13</flame_spread_parameter>
    <eff_heat_of_combustion>13.2</eff_heat_of_combustion>
    <soot_yield>0.015</soot_yield>
    <CO2_yield>1.27</CO2_yield>
    <H20_yield>0.442</H20_yield>
    <HCN_yield>0</HCN_yield>
   </wall_lining>
   <wall_substrate
    present="-1">
    <description>plasterboard</description>
    <thickness>16</thickness>
    <conductivity>0.16</conductivity>
    <specific_heat>900</specific_heat>
    <density>810</density>
   </wall_substrate>
   <ceiling_lining>
    <description>plasterboard</description>
    <thickness>16</thickness>
    <conductivity>0.16</conductivity>
    <specific_heat>900</specific_heat>
    <density>810</density>
    <emissivity>0.88</emissivity>
    <ceiling_cone_file>null.txt</ceiling_cone_file>
    <eff_heat_of_combustion>0</eff_heat_of_combustion>
    <soot_yield>0</soot_yield>
    <CO2_yield>0</CO2_yield>
    <H20_yield>0</H20_yield>
    <HCN_yield>0</HCN_yield>
   </ceiling_lining>
   <ceiling_substrate
    present="-1">
    <description>plasterboard</description>
    <thickness>16</thickness>
    <conductivity>0.16</conductivity>
    <specific_heat>900</specific_heat>
    <density>810</density>
```

```
    </ceiling_substrate>
    <floor_lining>
      <description>plasterboard</description>
      <thickness>16</thickness>
      <conductivity>0.16</conductivity>
      <specific_heat>900</specific_heat>
      <density>810</density>
      <emissivity>0.88</emissivity>
      <floor_cone_file>null.txt</floor_cone_file>
      <min_temp_spread>273</min_temp_spread>
      <flame_spread_parameter>0</flame_spread_parameter>
      <eff_heat_of_combustion>0</eff_heat_of_combustion>
      <soot_yield>0</soot_yield>
      <CO2_yield>0</CO2_yield>
      <H20_yield>0</H20_yield>
      <HCN_yield>0</HCN_yield>
    </floor_lining>
    <floor_substrate
      present="0" />
  </room>
 </rooms>
 <flamespread
  algorithm="2">
  <suppress_ceiling_hrr>False</suppress_ceiling_hrr>
  <flame_area_constant>0.0065</flame_area_constant>
  <flame_length_power>1</flame_length_power>
  <burner_width>0.8</burner_width>
  <wall_heat_flux>45</wall_heat_flux>
  <ceiling_heat_flux>35</ceiling_heat_flux>
  <ignite_next_room>False</ignite_next_room>
  <one_cone_curve>False</one_cone_curve>
  <ign_correlation>1</ign_correlation>
 </flamespread>
 <tenability>
  <monitor_height>1.5</monitor_height>
  <activity_level>Light</activity_level>
  <endpoint_radiation>2.5</endpoint_radiation>
  <endpoint_temp>873</endpoint_temp>
  <endpoint_visibility>10</endpoint_visibility>
  <endpoint_FED>1</endpoint_FED>
  <endpoint_convect>353</endpoint_convect>
  <FED_start_time>0</FED_start_time>
  <FED_end_time>1200</FED_end_time>
  <illumination>False</illumination>
 </tenability>
 <postflashover
  post="False"
  fluxcriteria="False">
  <FLED
    distribution=""
    value="0"
    mean="0"
    variance="0"
    lbound="0"
    ubound="0" />
  <fuel_thickness>0.05</fuel_thickness>
  <HoC_fuel
    distribution=""
    value="0"
    mean="0"
    variance="0"
    lbound="0"
    ubound="0" />
  <stick_spacing>0.1</stick_spacing>
 </postflashover>
 <chemistry>
  <nC>0.95</nC>
  <nH>2.4</nH>
  <nO>1</nO>
  <nN>0</nN>
  <fueltype>wood</fueltype>
  <hcn_calc>False</hcn_calc>
  <soot_alpha>2.5</soot_alpha>
  <soot_epsilon>1.2</soot_epsilon>
  <emission_coefficient>13.32</emission_coefficient>
  <pre_CO
    distribution=""
    value="0"
    mean="0"
    variance="0"
    lbound="0"
    ubound="0" />
  <post_CO>0.2</post_CO>
  <pre_soot
    distribution=""
    value="0"
    mean="0"
    variance="0"
    lbound="0"
    ubound="0" />
  <post_soot>0.2</post_soot>
  <CO_mode>False</CO_mode>
  <soot_mode>True</soot_mode>
 </chemistry>
 <fires>
  <fire_room>1</fire_room>
  <radiant_loss_fraction>0.3</radiant_loss_fraction>

<mass_loss_per_unit_area>0.011</mass_loss_per_unit_area>
  <!--plume, macaffrey=2, delichatsios=1-->
  <plume_algorithm>2</plume_algorithm>
 </fires>
 <hvents>
  <hvent>
    <room_1>1</room_1>
    <room_2>2</room_2>
    <id>1</id>
    <height>2</height>
    <width>0.8</width>
    <sill_height>0</sill_height>
    <open_time>0</open_time>
    <close_time>0</close_time>
    <wall_length_1>0</wall_length_1>
    <wall_length_2>0</wall_length_2>
    <face>1</face>
    <glassbreak
      autobreak="False" />
    <spillplume
      use_spillplume="0" />
  </hvent>
 </hvents>
 <vvents />
 <smoke_detectors />
 <fans />
</simulation>
```


distributions.xml


```
<?xml version="1.0" encoding="utf-8"?>
<Distributions>
  <Distribution>
    <id>1</id>
    <varname>Interior Temperature</varname>
    <units>K</units>
    <distribution>Triangular</distribution>
    <varvalue>295</varvalue>
    <mean>300</mean>
    <variance>5</variance>
```

```xml
  <lbound>288</lbound>
  <ubound>303</ubound>
  <mode>295</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>2</id>
  <varname>Exterior Temperature</varname>
  <units>K</units>
  <distribution>Normal</distribution>
  <varvalue>281</varvalue>
  <mean>281</mean>
  <variance>100</variance>
  <lbound>258</lbound>
  <ubound>318</ubound>
  <mode>293</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>3</id>
  <varname>Relative Humidity</varname>
  <units>-</units>
  <distribution>Triangular</distribution>
  <varvalue>0.5</varvalue>
  <mean>0.5</mean>
  <variance>0.0005</variance>
  <lbound>0.2</lbound>
  <ubound>0.75</ubound>
  <mode>0.5</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>4</id>
  <varname>Fire Load Energy Density</varname>
  <units>MJ/m2</units>
  <distribution>Normal</distribution>
  <varvalue>300</varvalue>
  <mean>300</mean>
  <variance>14400</variance>
  <lbound>10</lbound>
  <ubound>600</ubound>
  <mode>200</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>5</id>
  <varname>Heat of Combustion PFO</varname>
  <units>kJ/g</units>
  <distribution>None</distribution>
  <varvalue>20</varvalue>
  <mean>20</mean>
  <variance>3</variance>
  <lbound>10</lbound>
  <ubound>50</ubound>
  <mode>20</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>6</id>
  <varname>Soot Preflashover Yield</varname>
  <units>g/g</units>
  <distribution>None</distribution>
  <varvalue>0.1</varvalue>
  <mean>0.07</mean>
  <variance>0.01</variance>
  <lbound>0.02</lbound>
  <ubound>0.2</ubound>
  <mode>0.08</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>7</id>
  <varname>CO Preflashover Yield</varname>
  <units>g/g</units>
  <distribution>None</distribution>
  <varvalue>0.04</varvalue>
  <mean>0.05</mean>
  <variance>0.01</variance>
  <lbound>0.02</lbound>
  <ubound>0.2</ubound>
  <mode>0.04</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>8</id>
  <varname>Sprinkler Reliability</varname>
  <units>-</units>
  <distribution>None</distribution>
  <varvalue>0</varvalue>
  <mean>0.9</mean>
  <variance>0.01</variance>
  <lbound>0.9</lbound>
  <ubound>0.96</ubound>
  <mode>0.9</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>9</id>
  <varname>Sprinkler Suppression Probability</varname>
  <units>-</units>
  <distribution>None</distribution>
  <varvalue>0</varvalue>
  <mean>1</mean>
  <variance>0.01</variance>
  <lbound>0.5</lbound>
  <ubound>1</ubound>
  <mode>1</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>10</id>
  <varname>Sprinkler Cooling Coefficient</varname>
  <units>-</units>
  <distribution>none</distribution>
  <varvalue>1</varvalue>
  <mean>0</mean>
  <variance>0</variance>
  <lbound>0</lbound>
  <ubound>0</ubound>
  <mode>0</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
 <Distribution>
  <id>11</id>
  <varname>Fuel Heat of Gasification</varname>
  <units>kJ/g</units>
  <distribution>none</distribution>
  <varvalue>3</varvalue>
  <mean>0</mean>
  <variance>0</variance>
  <lbound>0</lbound>
  <ubound>0</ubound>
  <mode>0</mode>
  <alpha>0</alpha>
  <beta>0</beta>
 </Distribution>
</Distributions>
```

sprinklers.xml


```xml
<?xml version="1.0" encoding="utf-8"?>
<Sprinklers>
  <version>2012.09</version>
</Sprinklers>
```


items.xml


```xml
<?xml version="1.0" encoding="utf-8"?>
<Items>
  <version>2012.09</version>
  <Item>
    <id>1</id>
    <description>2 - PU foam spring-core mattress</description>
    <detaileddescription />
    <userlabel>2 - PU foam spring-core mattress</userlabel>
    <type>Generic</type>
    <length>1.9</length>
    <width>1.3</width>
    <height>0.2</height>
    <elevation>0.3</elevation>
    <mass>7.2</mass>
    <critical_flux_pilot>9.5</critical_flux_pilot>
    <critical_flux_auto>22</critical_flux_auto>
    <FTP_limit_pilot>481</FTP_limit_pilot>
    <FTP_limit_auto>427</FTP_limit_auto>
    <FTP_index_pilot>1</FTP_index_pilot>
    <FTP_index_auto>1</FTP_index_auto>
    <probability>0.5</probability>
    <hrr>0,0
460,170
500,1770
575,170
1000,0</hrr>
    <ignition_time>0</ignition_time>
    <max_num>1</max_num>
    <xleft>0.1</xleft>
    <ybottom>1</ybottom>
    <radiantlossfraction>0.3</radiantlossfraction>
    <constantA>0</constantA>
    <constantB>0</constantB>
    <idistribution>
      <varname>heat of combustion</varname>
      <value>26</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
    <idistribution>
      <varname>soot yield</varname>
      <value>0.1</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
    <idistribution>
      <varname>co2 yield</varname>
      <value>1.27</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
    <idistribution>
      <varname>Latent Heat of Gasification</varname>
      <value>0</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
  </Item>
  <Item>
    <id>2</id>
    <description>11 - PS/plywood/PU easy chair</description>
    <detaileddescription />
    <userlabel>11 - PS/plywood/PU easy chair</userlabel>
    <type>Generic</type>
    <length>0.8</length>
    <width>0.8</width>
    <height>0.8</height>
    <elevation>0</elevation>
    <mass>8.5</mass>
    <critical_flux_pilot>9.5</critical_flux_pilot>
    <critical_flux_auto>22</critical_flux_auto>
    <FTP_limit_pilot>481</FTP_limit_pilot>
    <FTP_limit_auto>427</FTP_limit_auto>
    <FTP_index_pilot>1</FTP_index_pilot>
    <FTP_index_auto>1</FTP_index_auto>
    <probability>0.5</probability>
    <hrr>0,0
75,25
150,125
240,960
300,850
600,120
1000,0</hrr>
    <ignition_time>0</ignition_time>
    <max_num>2</max_num>
    <xleft>0.2</xleft>
    <ybottom>0.1</ybottom>
    <radiantlossfraction>0.3</radiantlossfraction>
    <constantA>0</constantA>
    <constantB>0</constantB>
    <idistribution>
      <varname>heat of combustion</varname>
      <value>33</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
```

```
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
    <idistribution>
      <varname>soot yield</varname>
      <value>0.1</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
    <idistribution>
      <varname>co2 yield</varname>
      <value>1.27</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
    <idistribution>
      <varname>Latent Heat of Gasification</varname>
      <value>0</value>
      <distribution>none</distribution>
      <mean>0</mean>
      <variance>0</variance>
      <lbound>0</lbound>
      <ubound>0</ubound>
      <mode>0</mode>
      <alpha>0</alpha>
      <beta>0</beta>
    </idistribution>
  </Item>
  <Item>
    <id>3</id>
    <description>21 - Metal frame chair with PU
cushions</description>
    <detaileddescription />
    <userlabel>21 - Metal frame chair with PU
cushions</userlabel>
    <type>Generic</type>
    <length>0.5</length>
    <width>0.5</width>
    <height>0.5</height>
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850,150
860,290
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350,200
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1270,50
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1200,120
1800,50
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<alpha>0</alpha>
<beta>0</beta>
</idistribution>
</Item>
</Items>

A5 MDF cone calorimeter data

Cone calorimeter data for 18 mm thick MDF by Li [57]. Format is suitable for input in BRANZFIRE/ B-RISK materials database.

KaisMDF.txt

```
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"Heat Flux",35
"Number of HRR Data Pairs",273
"sec,kw/m2"
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20,225.4
25,208.2
30,199.3
35,193.7
40,172.3
45,165.4
50,156.2
55,154.8
60,146.6
65,140.3
70,132.7
75,129.0
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85,118.4
90,119.2
95,113.4
100,110.7
105,114.2
110,107.0
115,108.1
120,104.7
125,106.4
130,106.5
135,105.3
140,105.5
145,106.2
150,109.2
155,107.8
160,101.9
165,102.5
170,99.5
175,102.1
180,92.5
185,90.5
190,90.9
195,86.9
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205,83.5
210,78.4
215,74.7
220,70.4
225,70.5
230,74.2
235,69.7
240,67.8
245,64.1
250,68.0
255,74.9
260,68.7
265,67.9
270,68.5
275,63.7
280,62.7
285,67.2
290,66.3
295,64.9
300,68.2
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310,63.8
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355,61.5
360,63.6
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375,66.8
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390,67.1
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630,107.1
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645,115.5
650,119.6
655,121.6
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680,131.1
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695,141.5
700,141.6
705,139.1
710,144.2
715,142.8
720,150.7
725,152.4
730,152.5
735,148.2
740,151.1
745,154.5
750,158.2
755,162.6
760,165.9
765,168.8
770,170.2
775,160.4
780,174.6
785,177.9
790,182.8
795,184.1
800,187.7
805,188.5
810,199.6
815,196.3
820,189.3
825,169.1
830,149.1
835,134.8
840,118.0
845,106.6
850,91.4
855,81.2
860,76.8
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870,62.7
875,59.0
880,54.4
885,50.5
890,50.4
895,47.1
900,49.6
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1070,36.3
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1145,30.4
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1175,31.5
1180,32.0
1185,32.4
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1330,32.2
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90,153.8
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675,171.5
680,168.1
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"sec,kw/m2"
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25,299.0
30,262.8
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40,216.4
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50,201.0
55,194.5
60,183.5
65,184.4
70,183.8
75,173.2
80,180.8
85,178.2
90,181.5
95,173.0
100,171.7
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295,111.7
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770,50.2
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785,48.6
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825,50.4
830,47.5
835,49.6
840,49.1
845,49.2
850,49.3
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860,48.4
865,49.5
870,46.2
875,47.9
880,48.8
885,44.7
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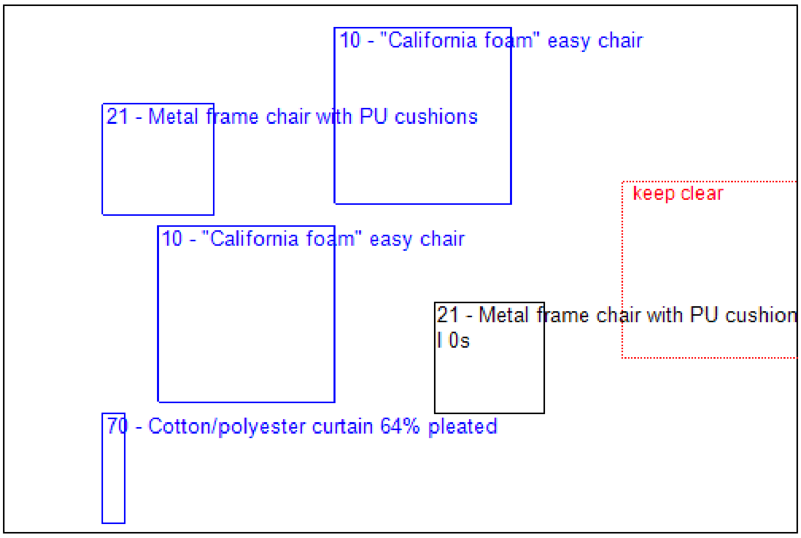
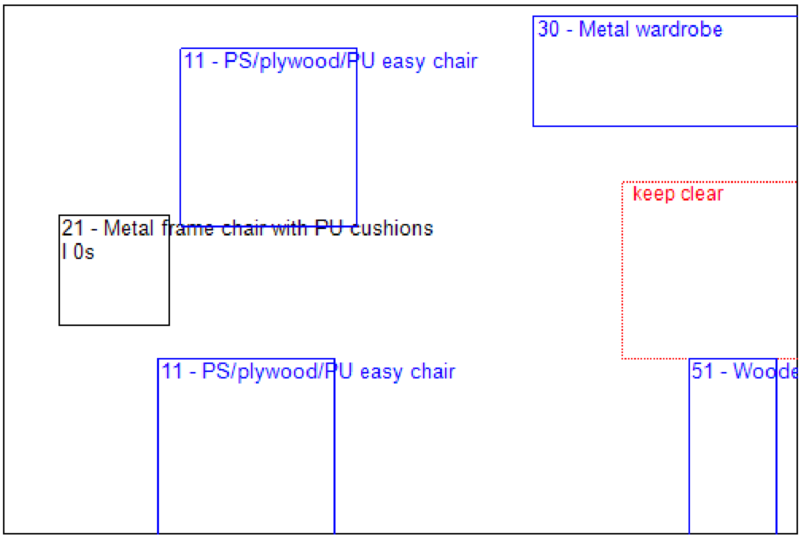
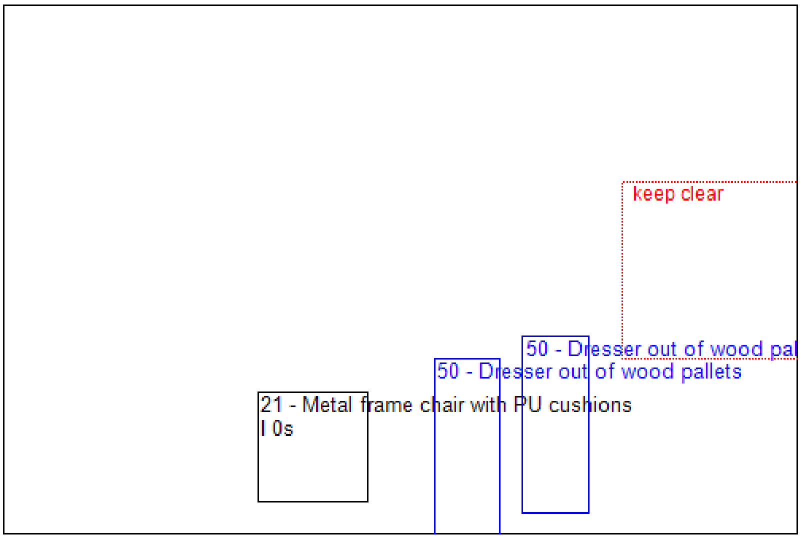
895,42.9
900,46.8
905,44.1
910,43.3
915,45.4
920,43.8
925,44.2
930,43.6
935,42.4
940,43.1
945,45.9
950,43.6
"Ignition Data"
"Number of Pairs",6
"flux kw/m2,ignition time sec, peak hrr kw/m2"
35,59,233.2
35,67,318
50,30,285.9
50,28,388.4
65,13,345.1
65,15,445.2
"Flame Spread Parameter",0
"Min Surface Temp For Spread",0
"Effective Heat of Combustion","0"

A6 Sample fuel load configurations generated by the DFG

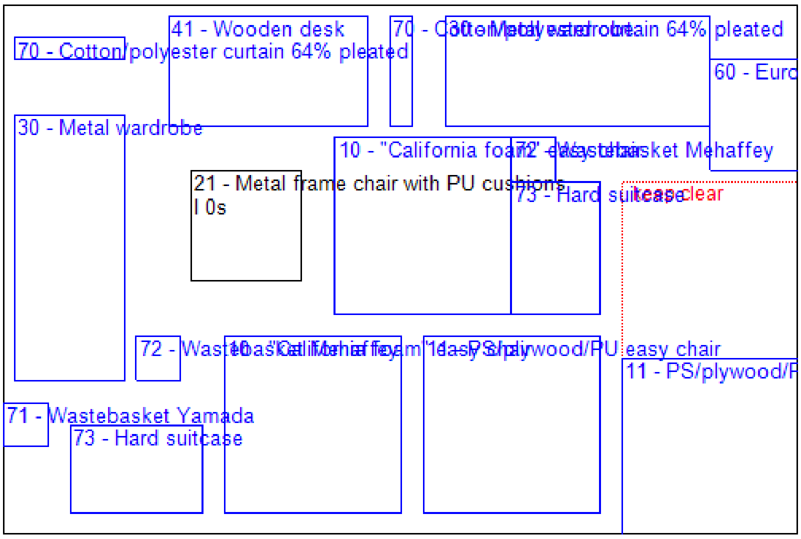
Target FLED 100 MJ/m^2:

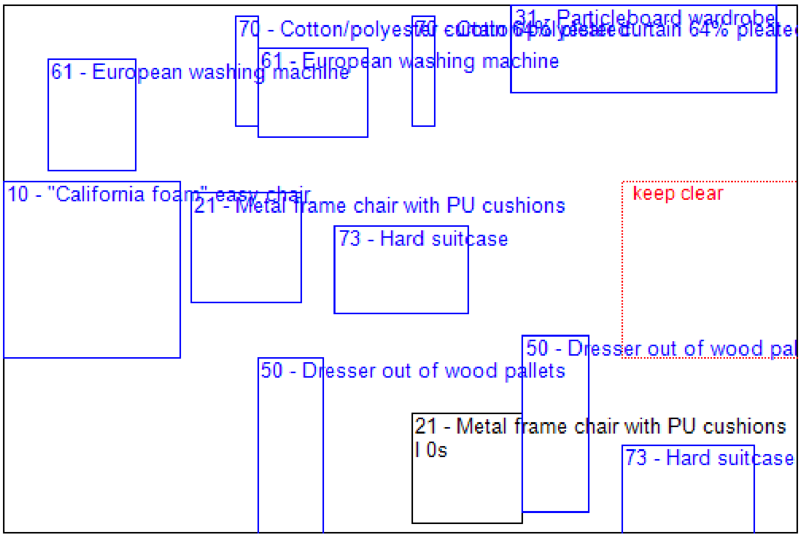


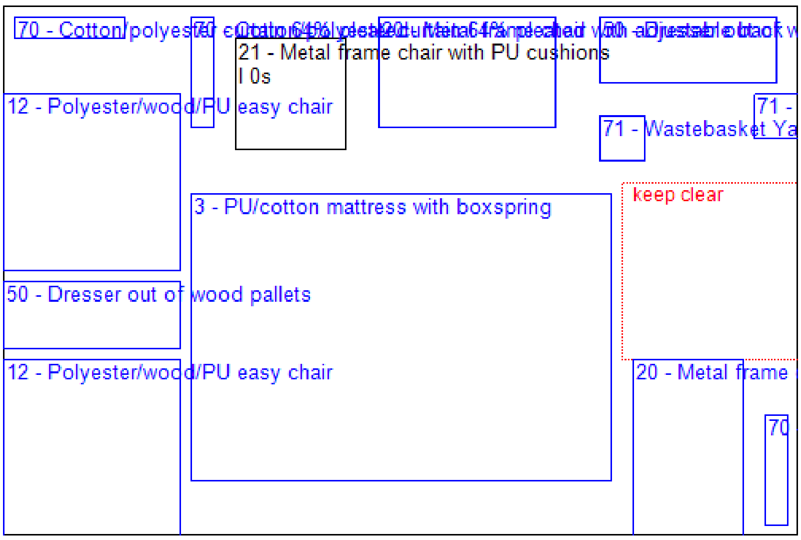




Target FLED 400 MJ/m^2:







A7 Sample log files from parametric study

From simulations in Section 5.2.

Case A:

Item 2 first ignited:

```
Simulation Finished.
485 sec. Flashover in Room 1.
Iteration 1
```

Item 11 first ignited:

```
Simulation Finished.
686 sec. Flashover in Room 1.
287 sec. Item 2 61 - European washing machine ignited (piloted ign).
201 sec. Item 5 2 - PU foam spring-core mattress ignited (piloted ign).
184 sec. Item 3 70 - Cotton/polyester curtain 64% pleated ignited (piloted ign).
Iteration 1
```

Item 21 first ignited:

```
Simulation Finished.
711 sec. Flashover in Room 1.
271 sec. Item 9 61 - European washing machine ignited (piloted ign).
228 sec. Item 2 2 - PU foam spring-core mattress ignited (piloted ign).
154 sec. Item 4 41 - Wooden desk ignited (piloted ign).
Iteration 1
```

Item 41 first ignited:

```
Simulation Finished.
717 sec. Flashover in Room 1.
238 sec. Item 10 2 - PU foam spring-core mattress ignited (piloted ign).
169 sec. Item 3 61 - European washing machine ignited (piloted ign).
100 sec. Item 7 21 - Metal frame chair with PU cushions ignited (piloted ign).
Iteration 1
```

Item 50 first ignited:

```
Simulation Finished.
147 sec. Flashover in Room 1.
128 sec. Item 2 73 - Hard suitcase ignited (piloted ign).
54 sec. Item 10 60 - European television set ignited (piloted ign).
Iteration 1
```

Item 60 first ignited:

```
Simulation Finished.
291 sec. Flashover in Room 1.
224 sec. Item 9 73 - Hard suitcase ignited (piloted ign).
162 sec. Item 3 50 - Dresser out of wood pallets ignited (piloted ign).
Iteration 1
```

Item 61 first ignited:

```
Simulation Finished.
833 sec. Flashover in Room 1.
678 sec. Item 3 2 - PU foam spring-core mattress ignited (piloted ign).
676 sec. Item 4 11 - PS/plywood/PU easy chair ignited (piloted ign).
552 sec. Item 7 21 - Metal frame chair with PU cushions ignited (piloted ign).
514 sec. Item 9 41 - Wooden desk ignited (piloted ign).
Iteration 1
```

Item 70 first ignited:

```
Simulation Finished.
526 sec. Flashover in Room 1.
317 sec. Item 5 61 - European washing machine ignited (piloted ign).
49 sec. Item 10 2 - PU foam spring-core mattress ignited (piloted ign).
33 sec. Item 8 11 - PS/plywood/PU easy chair ignited (piloted ign).
Iteration 1
```

Item 71 first ignited:

```
Simulation Finished.
Iteration 1
```

Item 73 first ignited:

```
Simulation Finished.
Iteration 1
```

Case B:

Item 2 first ignited:

```
Simulation Finished.
62 sec. Flashover in Room 1.
56 sec. Wall in Room 1 has ignited.
56 sec. Ceiling in Room 1 ignited.
Iteration 1
```

Item 11 first ignited:

```
Simulation Finished.
69 sec. Flashover in Room 1.
58 sec. Wall in Room 1 has ignited.
58 sec. Ceiling in Room 1 ignited.
Iteration 1
```

Item 21 first ignited:

```
Simulation Finished.
348 sec. Flashover in Room 1.
271 sec. Item 6 61 - European washing machine ignited (piloted ign).
228 sec. Item 10 2 - PU foam spring-core mattress ignited (piloted ign).
202 sec. Item 4 41 - Wooden desk ignites wall.
154 sec. Item 4 41 - Wooden desk ignited (piloted ign).
Iteration 1
```

Item 41 first ignited:

```
Simulation Finished.
234 sec. Flashover in Room 1.
231.0 sec: Too Many Steps in Derk_Spread_fireroom
169 sec. Item 3 61 - European washing machine ignited (piloted ign).
100 sec. Item 9 21 - Metal frame chair with PU cushions ignited (piloted ign).
50 sec. Wall in Room 1 has ignited.
Iteration 1
```

Item 50 first ignited:

```
Simulation Finished.
91 sec. Flashover in Room 1.
87 sec. Ceiling in Room 1 ignited.
54 sec. Item 6 60 - European television set ignited (piloted ign).
6 sec. Wall in Room 1 has ignited.
Iteration 1
```

Item 60 first ignited:

```
Simulation Finished.
185 sec. Flashover in Room 1.
162 sec. Item 2 50 - Dresser out of wood pallets ignited (piloted ign).
132 sec. Ceiling in Room 1 ignited.
55 sec. Wall in Room 1 has ignited.
Iteration 1
```

Item 61 first ignited:

```
Simulation Finished.
680 sec. Flashover in Room 1.
678 sec. Item 10 2 - PU foam spring-core mattress ignited (piloted ign).
676 sec. Item 2 11 - PS/plywood/PU easy chair ignited (piloted ign).
552 sec. Item 3 21 - Metal frame chair with PU cushions ignited (piloted ign).
514 sec. Item 7 41 - Wooden desk ignited (piloted ign).
103 sec. Wall in Room 1 has ignited.
Iteration 1
```

Item 70 first ignited:

```
Simulation Finished.
255 sec. Flashover in Room 1.
252 sec. Item 4 2 - PU foam spring-core mattress ignites ceiling.
49 sec. Item 4 2 - PU foam spring-core mattress ignited (piloted ign).
34 sec. Wall in Room 1 has ignited.
33 sec. Item 3 11 - PS/plywood/PU easy chair ignited (piloted ign).
Iteration 1
```

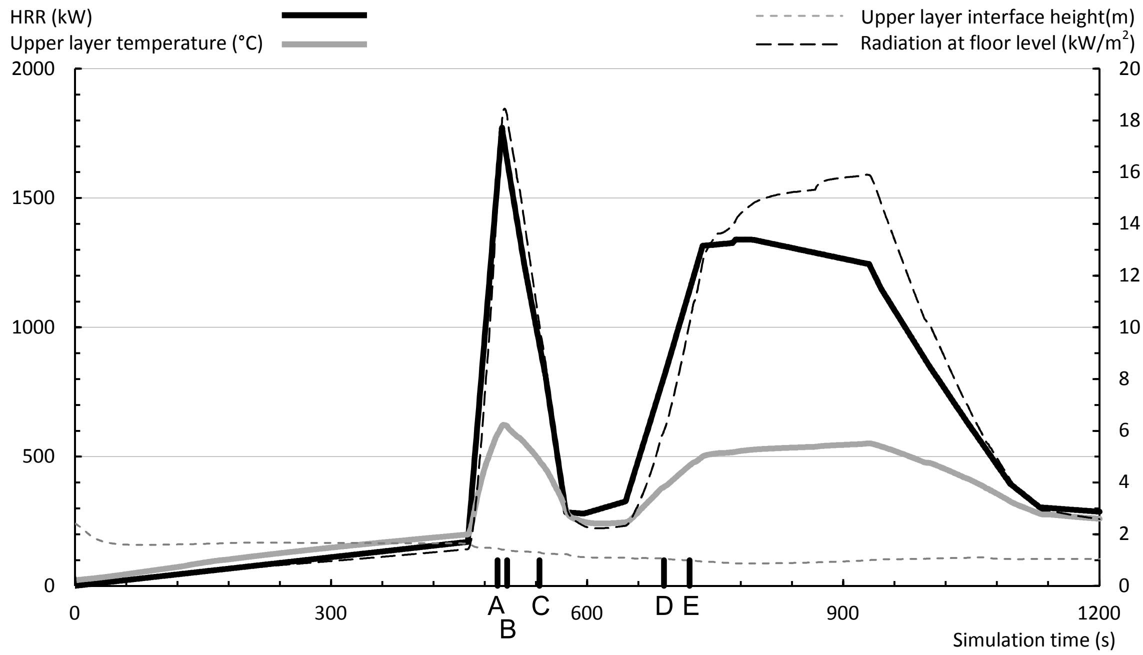
Item 71 first ignited:

```
Simulation Finished.
322 sec. Flashover in Room 1.
Ceiling in Room 1 has ignited at 153 seconds (due to wall burning).
14 sec. Wall in Room 1 has ignited.
Iteration 1
```

Item 73 first ignited:

```
Simulation Finished.
828 sec. Flashover in Room 1.
824.0 sec: Too Many Steps in Derk_Spread_fireroom
Ceiling in Room 1 has ignited at 740 seconds (due to wall burning).
65 sec. Wall in Room 1 has ignited.
Iteration 1
```

A8 Output graph of parametric study, flashover criterion comparison, Case A, item 2 first ignited



Log file:

A 495 sec. Item 3 11 - PS/plywood/PU easy chair ignited (piloted ign).

B 506 sec. Item 6 70 - Cotton/polyester curtain 64% pleated ignited (piloted ign).

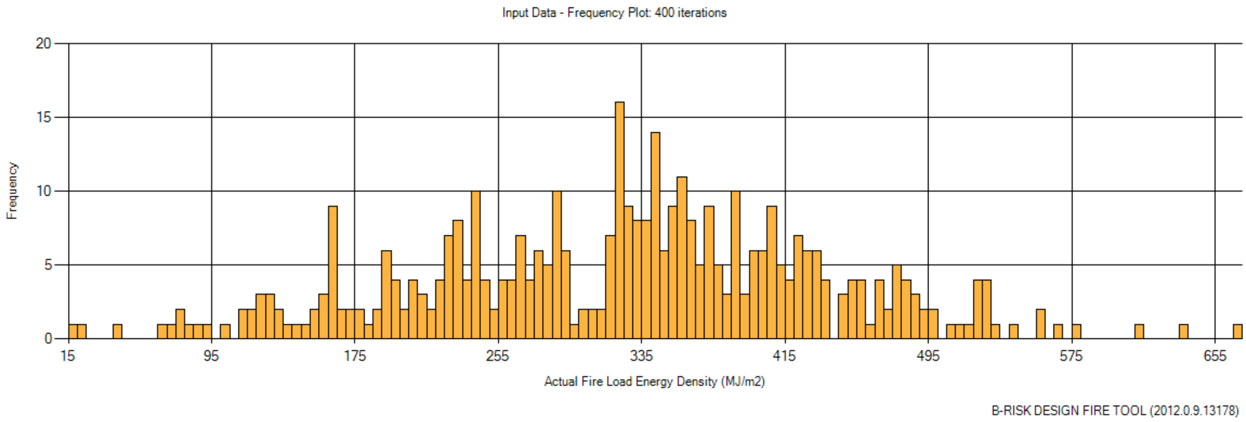
C 544 sec. Item 7 21 - Metal frame chair with PU cushions ignited (piloted ign).

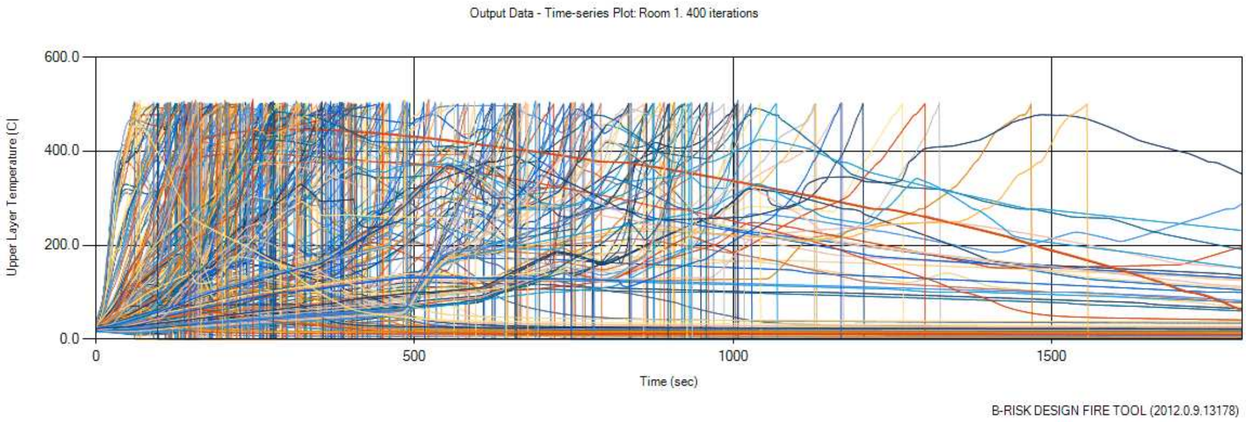
D 690 sec. Item 9 41 - Wooden desk ignited (piloted ign).

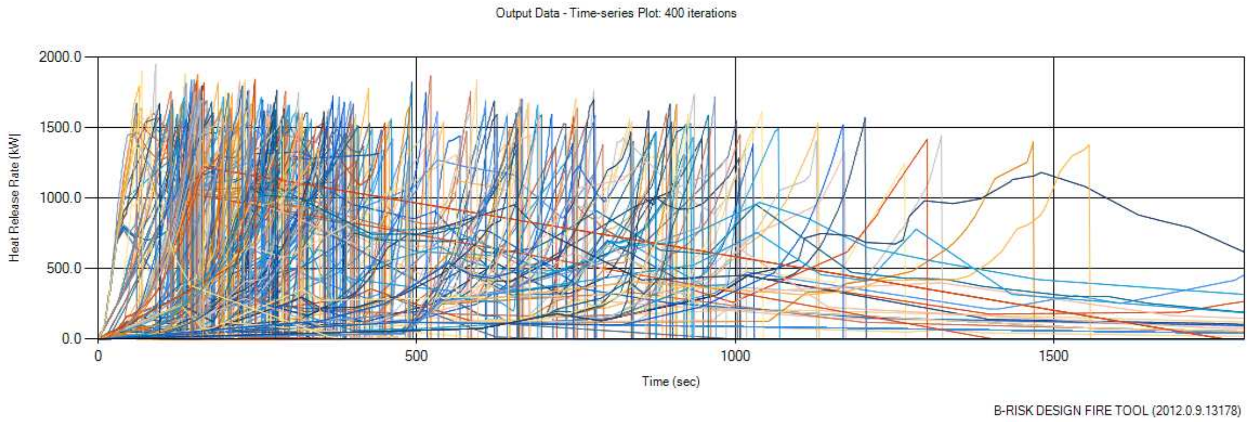
E 720 sec. Item 10 61 - European washing machine ignited (piloted ign).

A9 Output graphs of final simulations

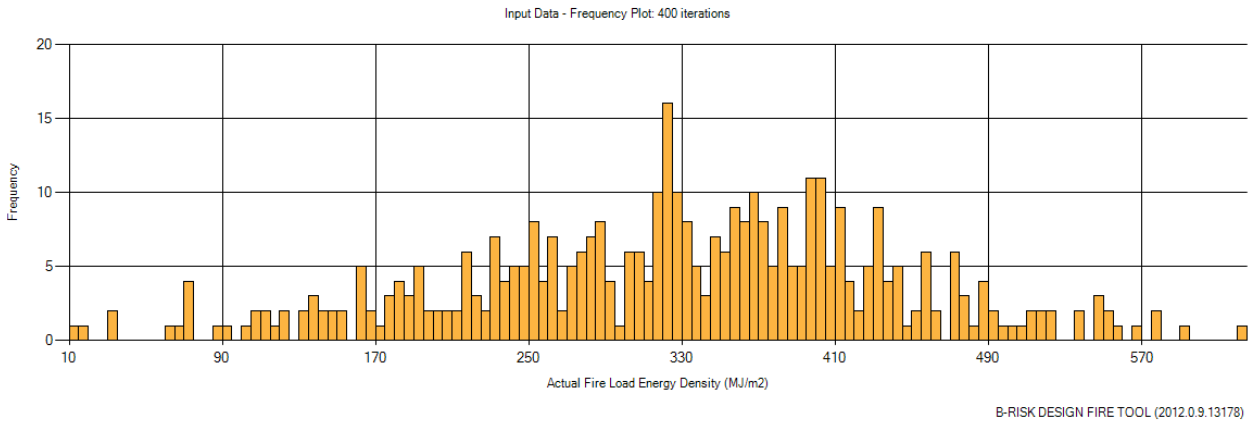
Section 6.2, Case A (graphs generated by B-RISK)

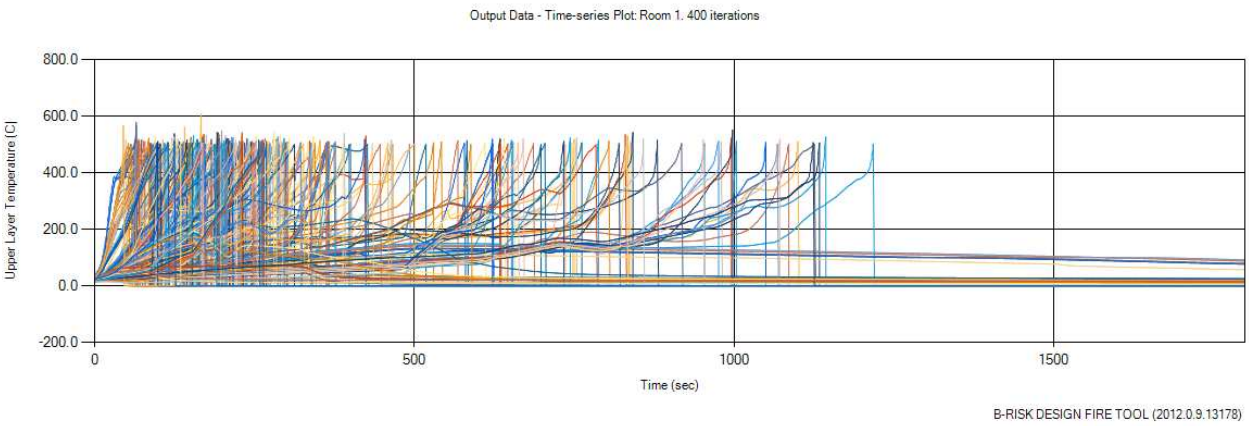


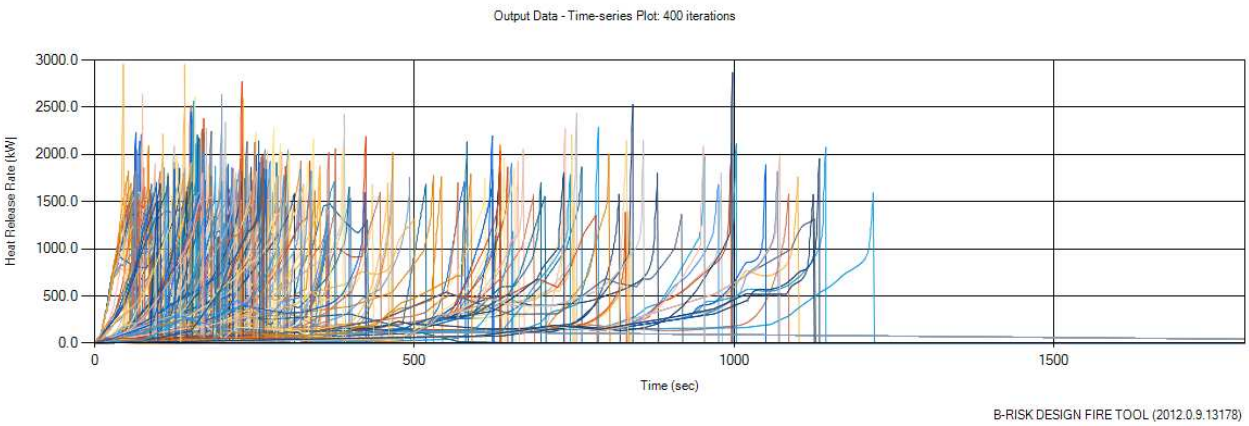




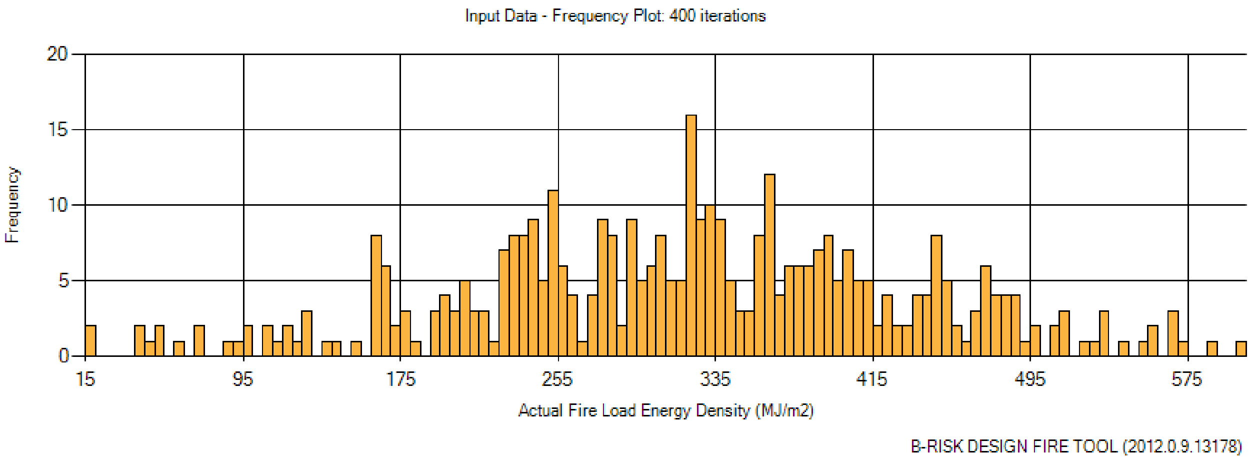
Section 6.2, Case B (graphs generated by B-RISK)

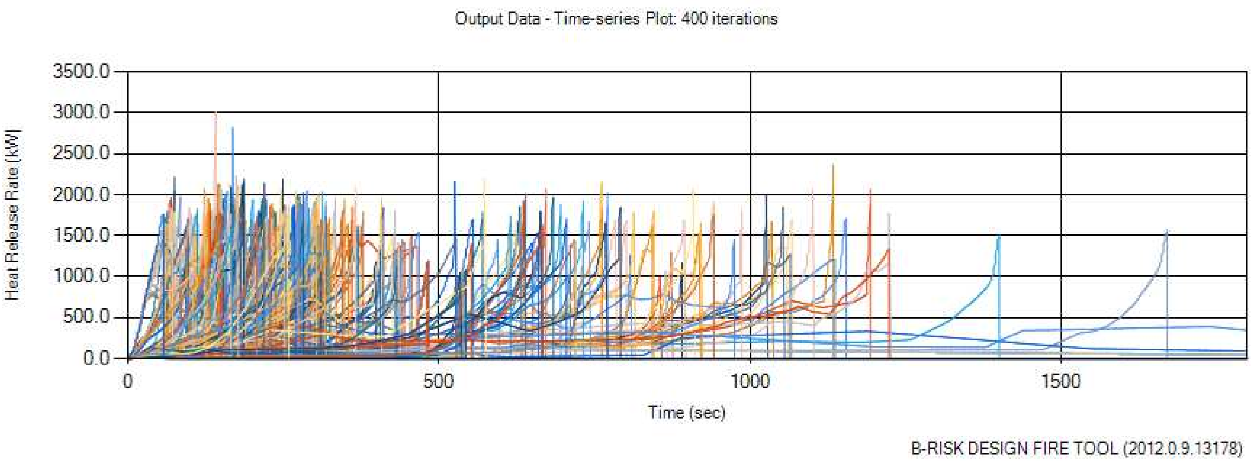






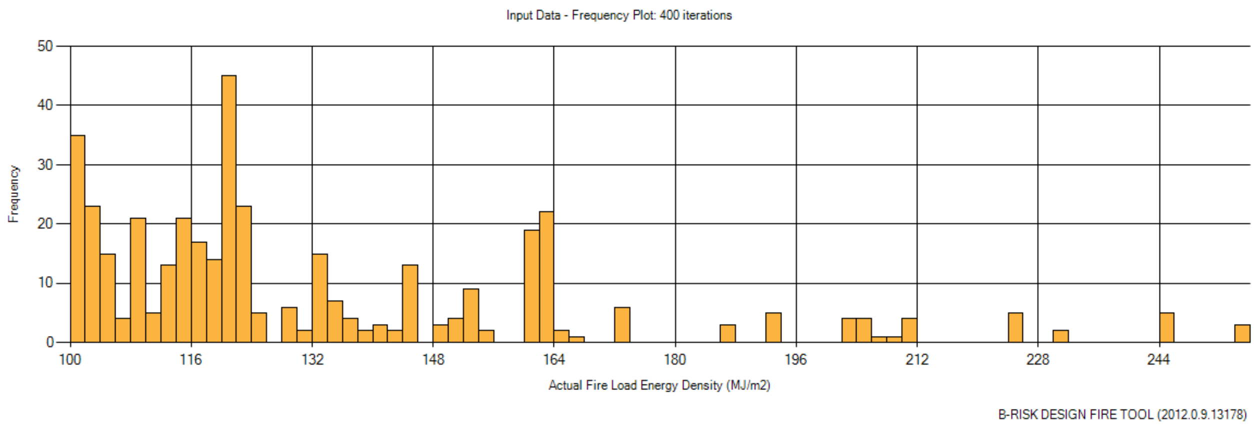
Section 6.2, Case C (graphs generated by B-RISK)

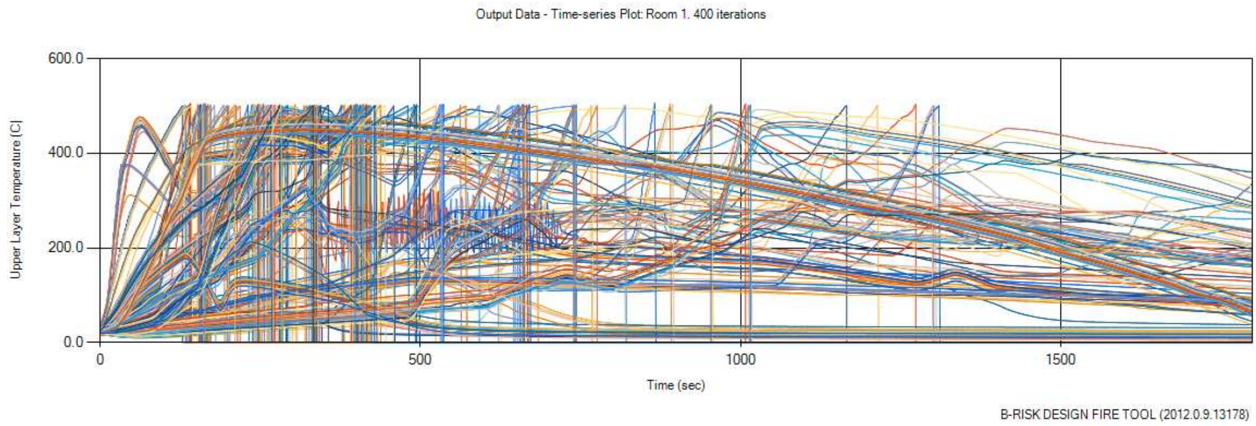


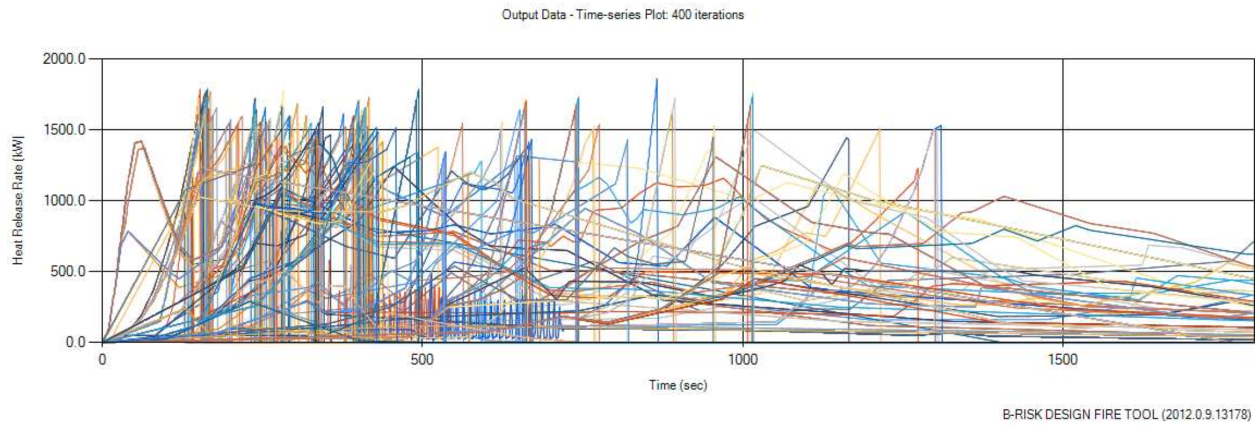


Section 6.3, Case A, target FLED = 100 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 134 MJ/m^2, standard deviation = 30 MJ/m^2, coefficient of variation = 22%

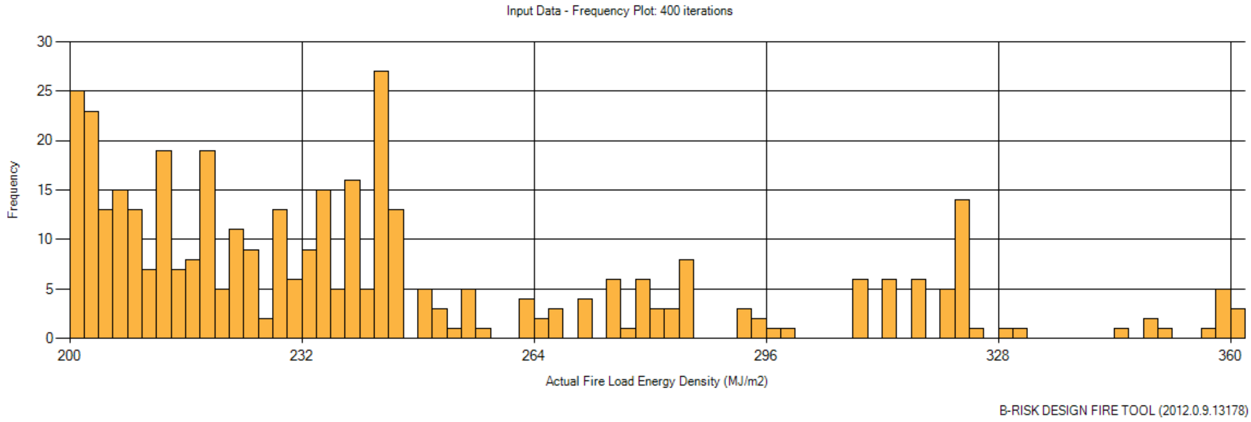


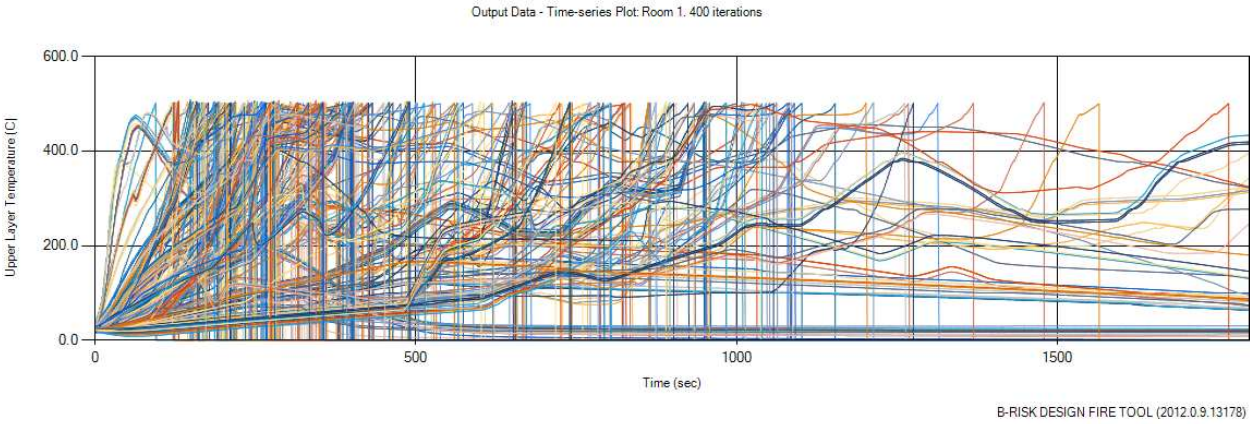


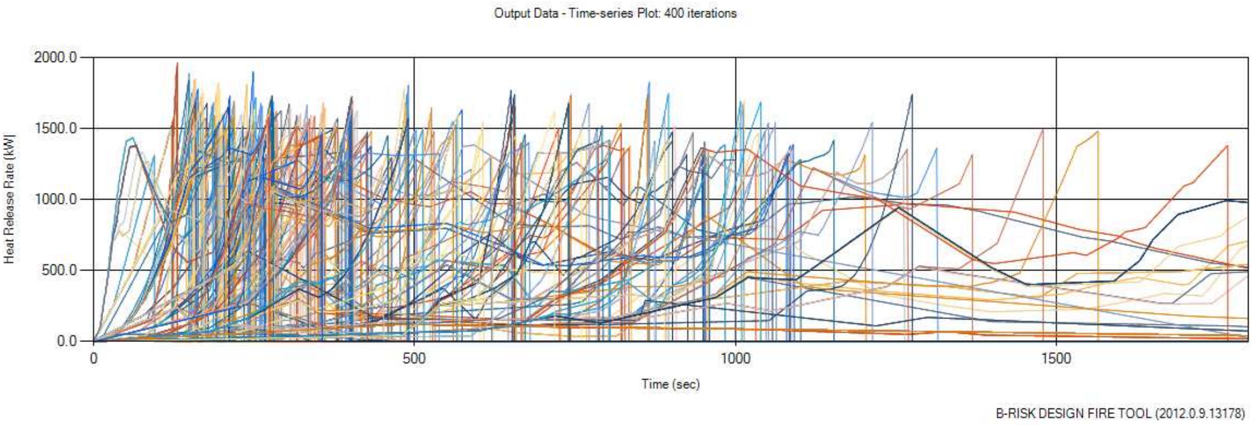


Section 6.3, Case A, target FLED = 200 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 243 MJ/m^2, standard deviation = 41 MJ/m^2, coefficient of variation = 17%

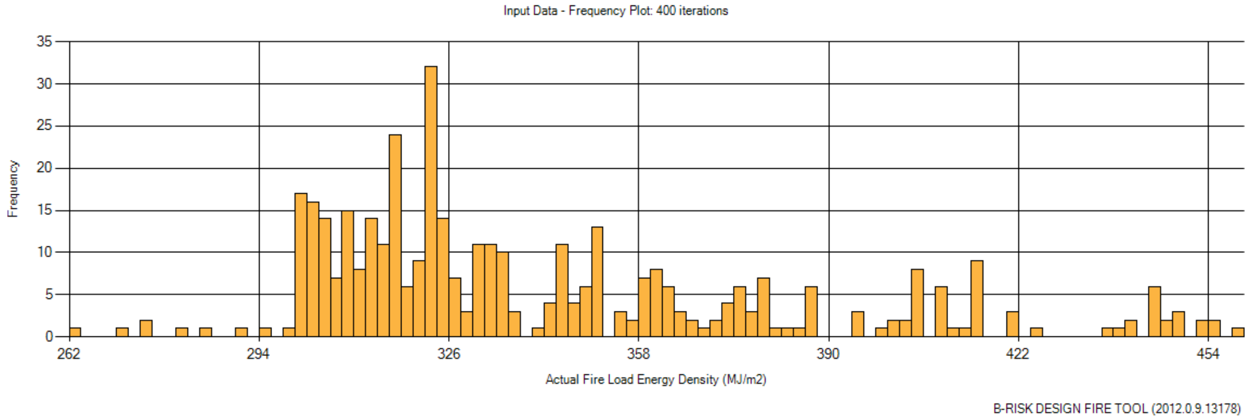


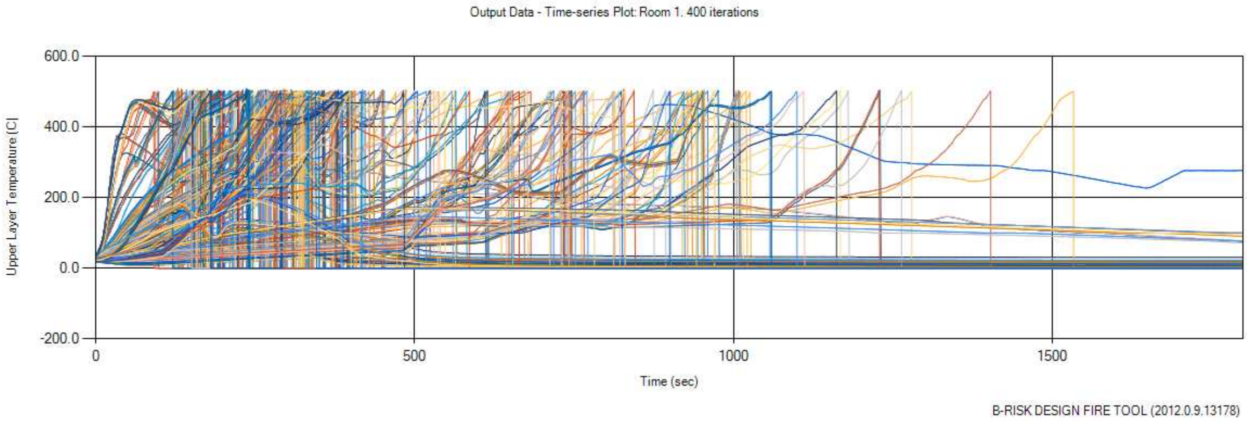


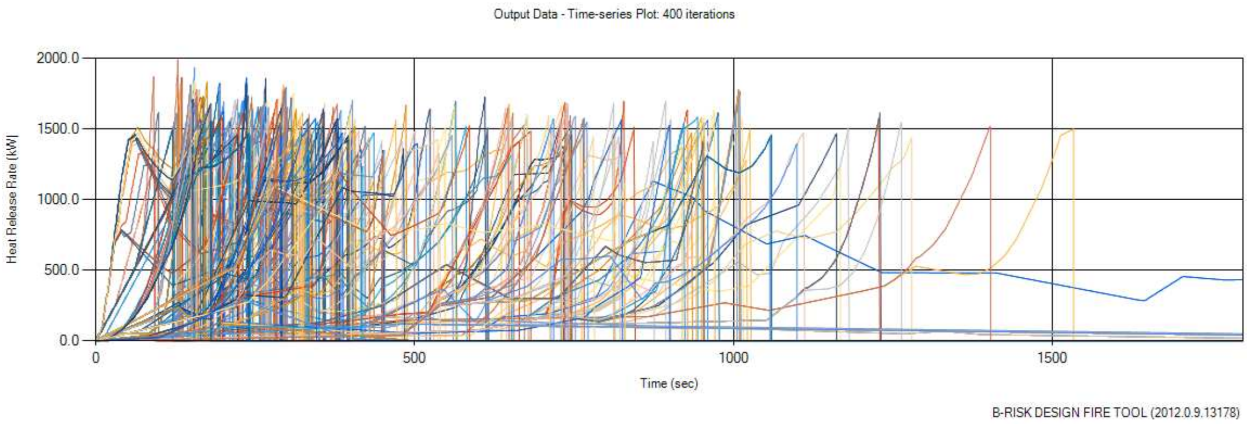


Section 6.3, Case A, target FLED = 300 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 343 MJ/m^2, standard deviation = 40 MJ/m^2, coefficient of variation = 12%

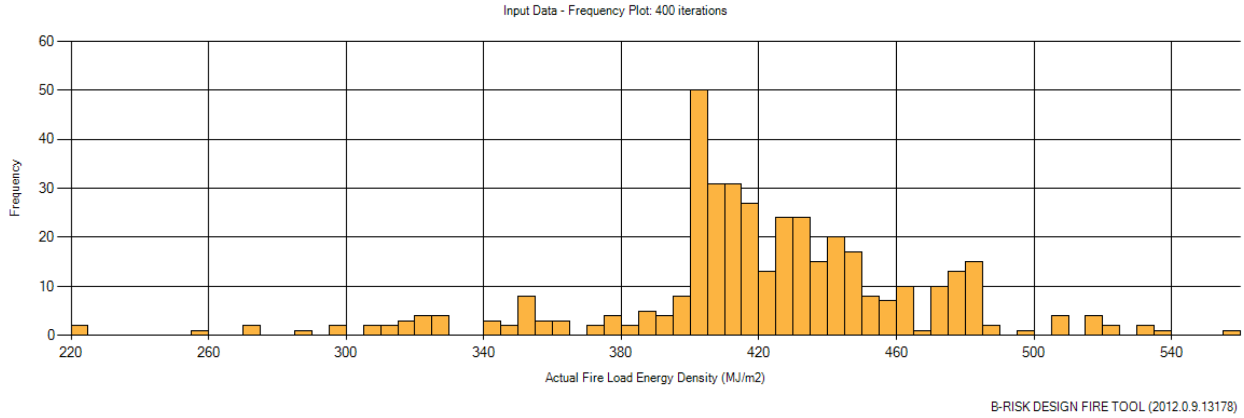


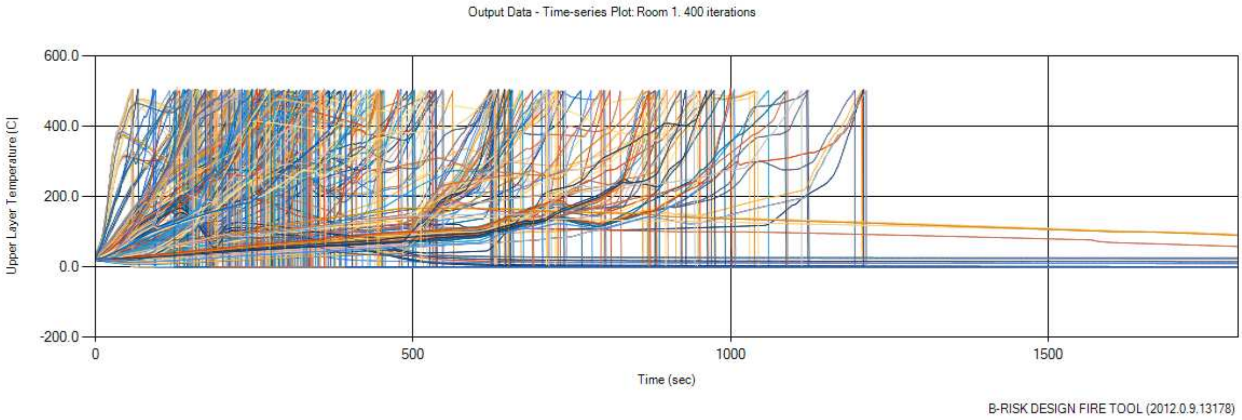


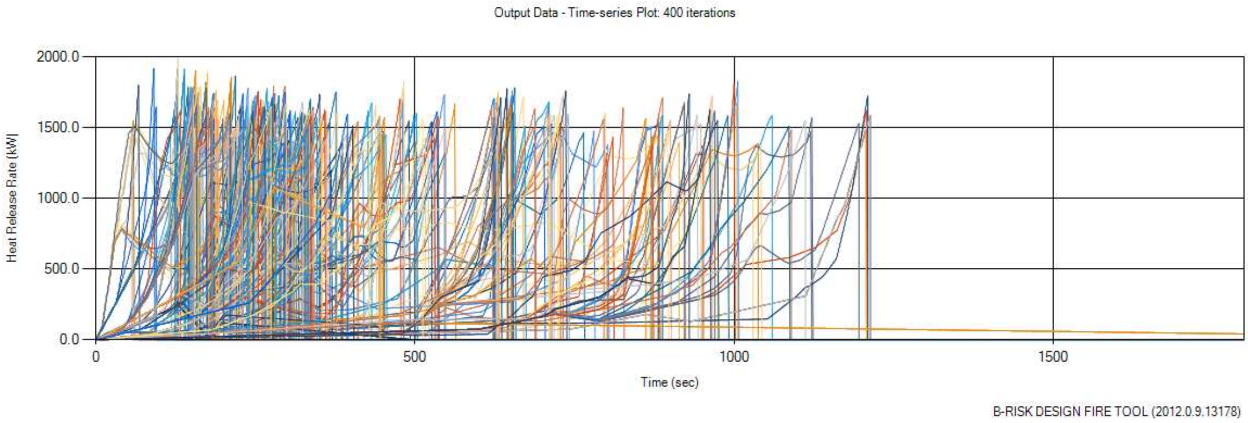


Section 6.3, Case A, target FLED = 400 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 420 MJ/m^2, standard deviation = 46 MJ/m^2, coefficient of variation = 11%

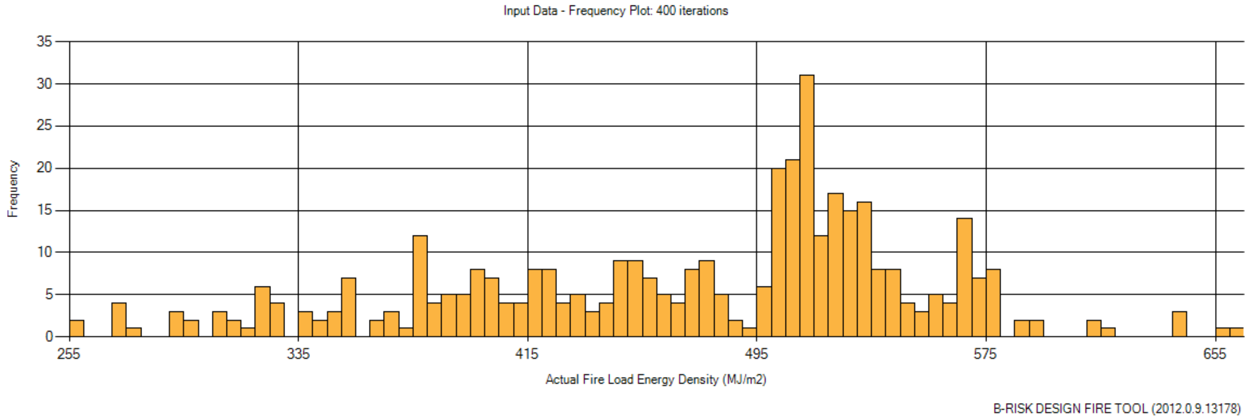


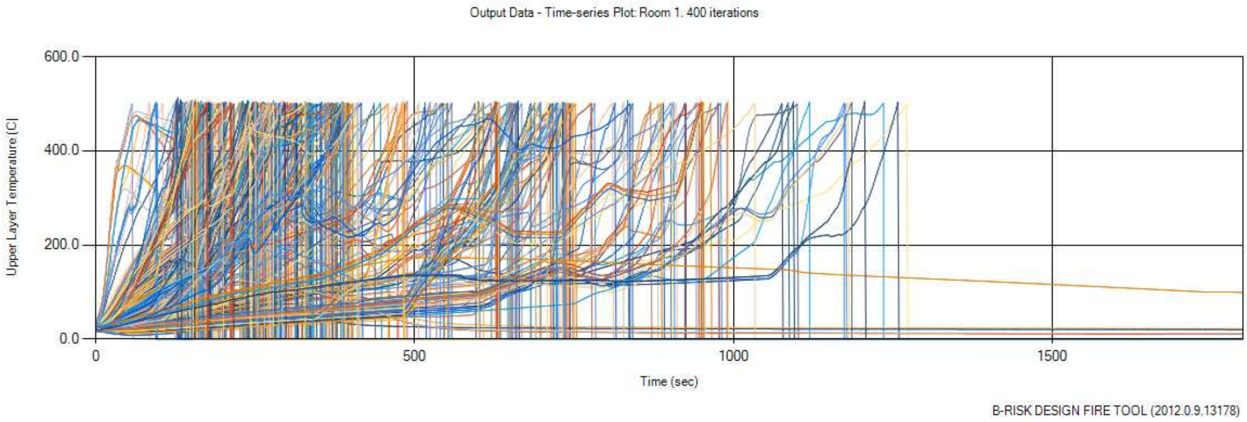


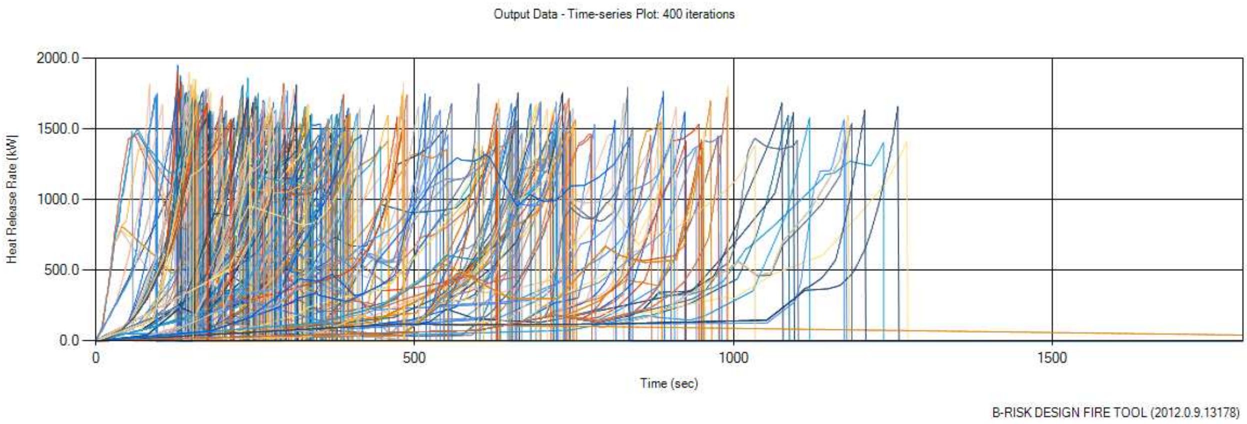


Section 6.3, Case A, target FLED = 500 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 472 MJ/m^2, standard deviation = 80 MJ/m^2, coefficient of variation = 17%

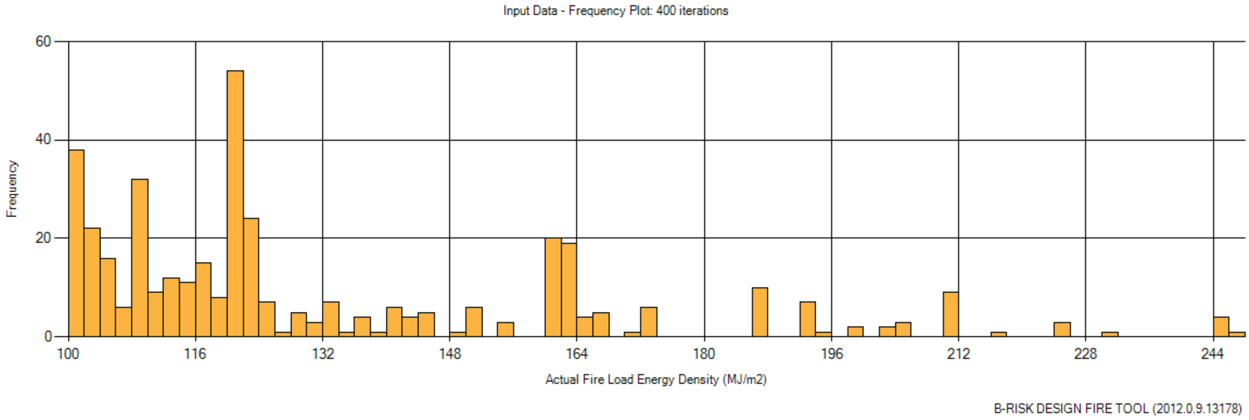


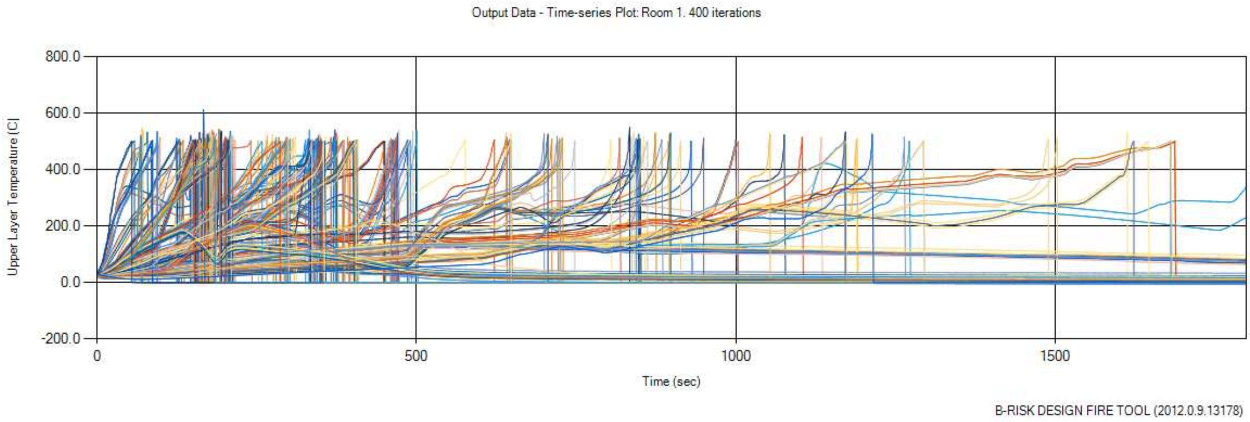


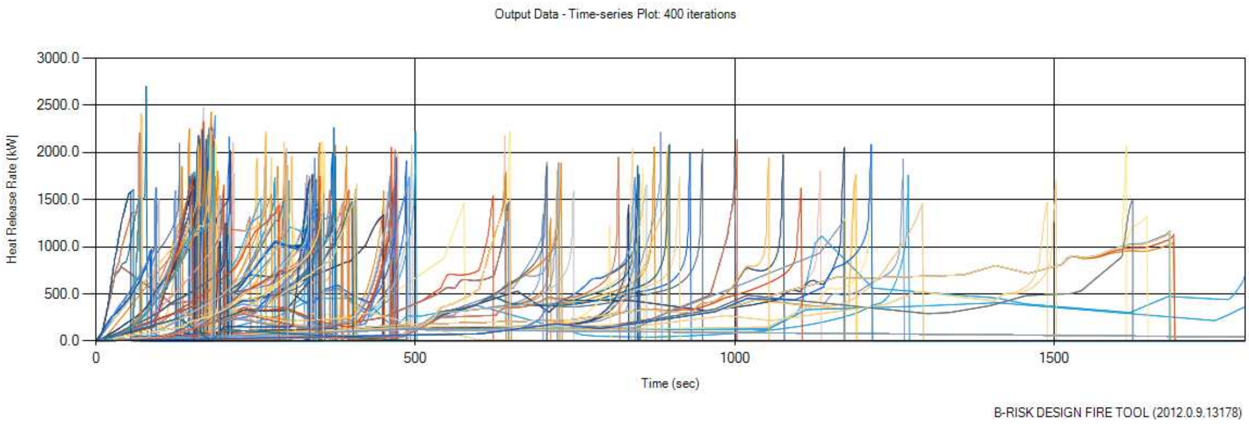


Section 6.3, Case B, target FLED = 100 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 133 MJ/m^2, standard deviation = 33 MJ/m^2, coefficient of variation = 25%

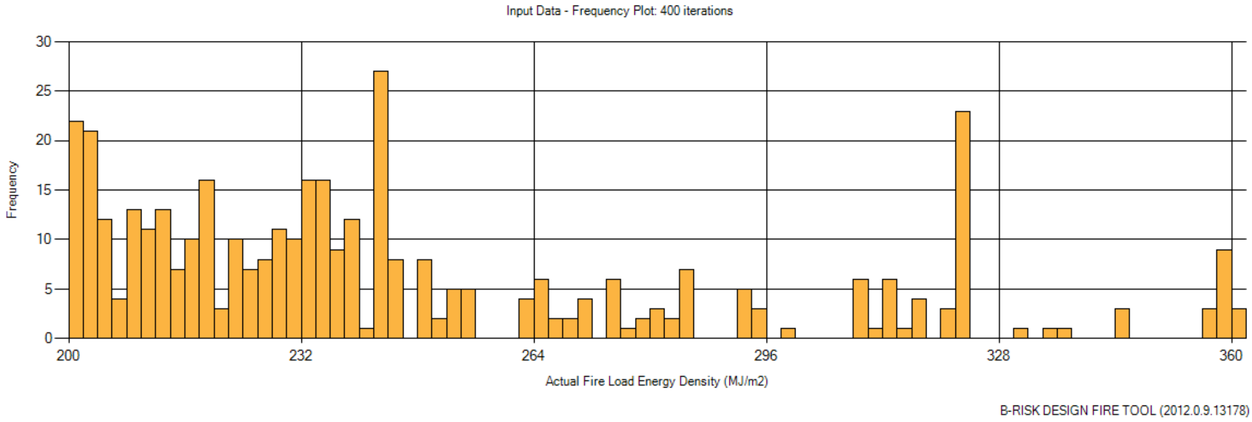


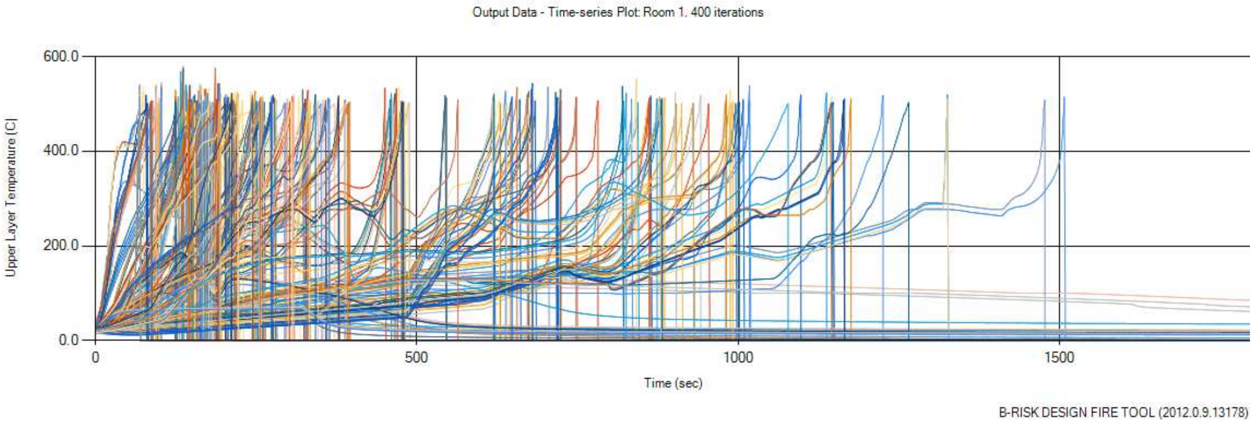


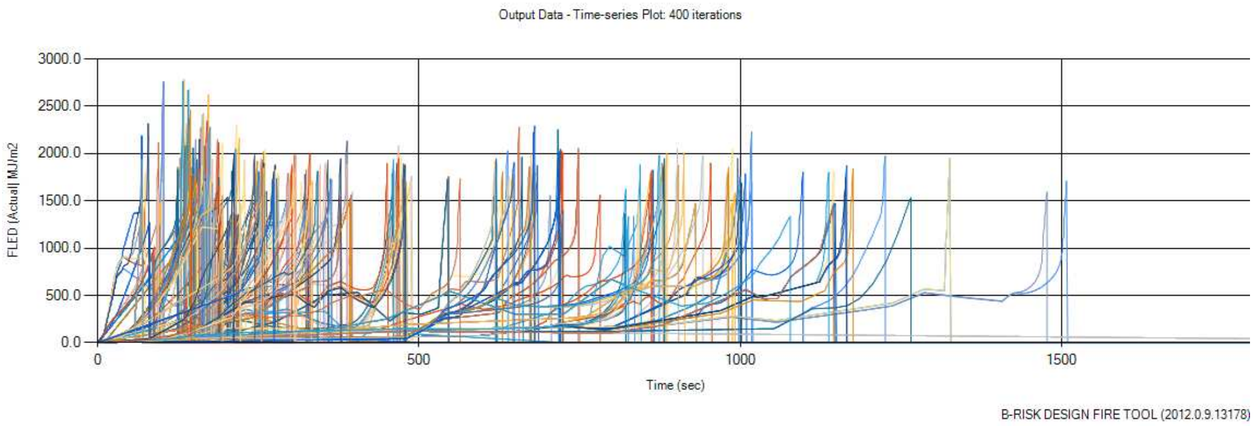


Section 6.3, Case B, target FLED = 200 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 248 MJ/m^2, standard deviation = 43 MJ/m^2, coefficient of variation = 17%

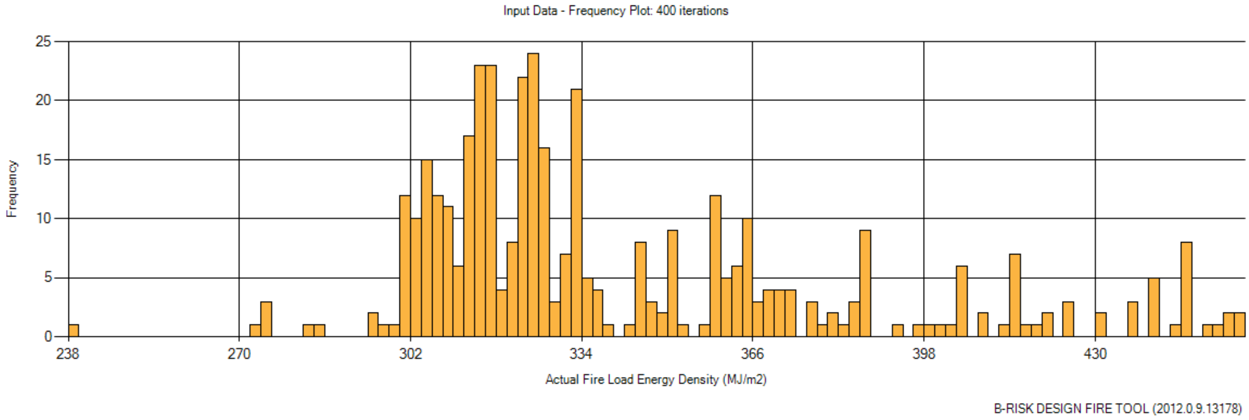


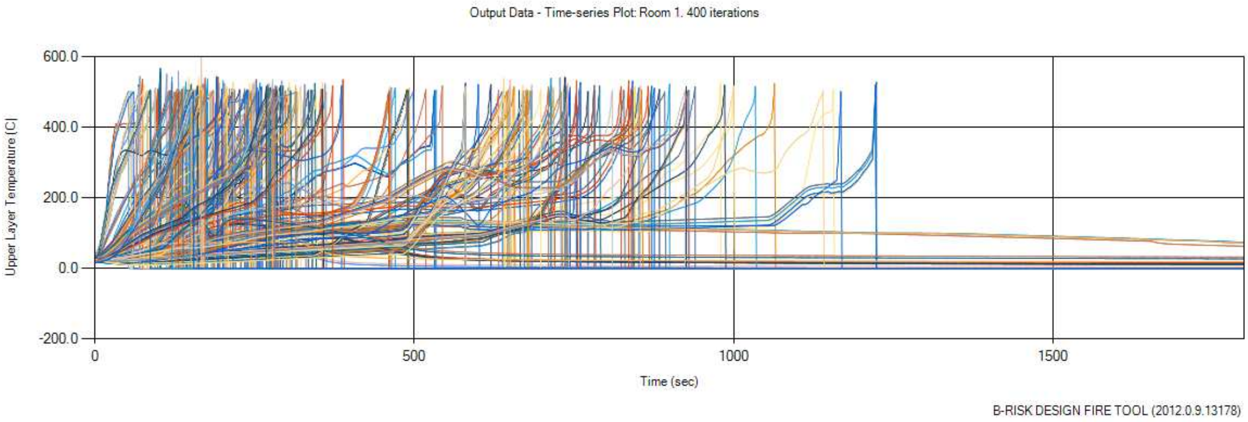


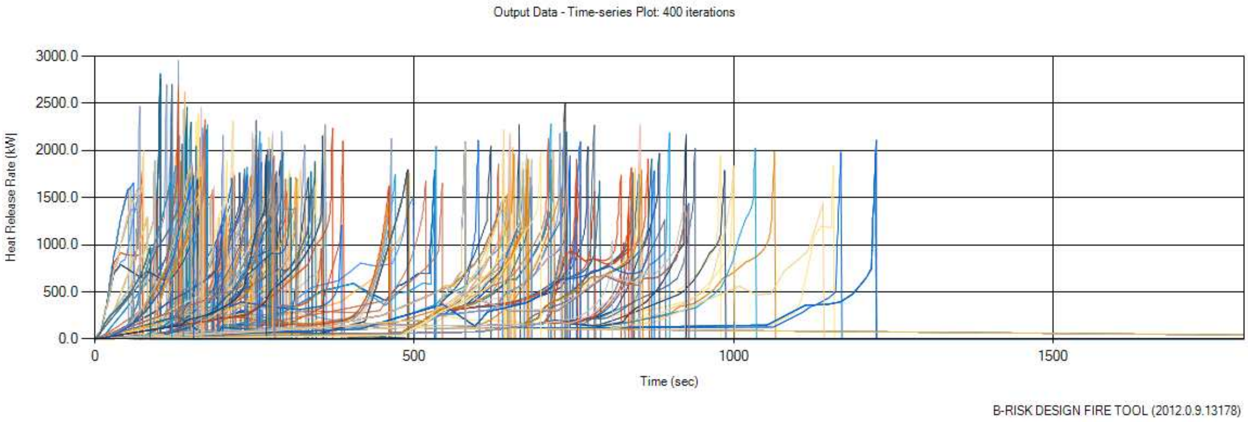


Section 6.3, Case B, target FLED = 300 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 342 MJ/m^2, standard deviation = 41 MJ/m^2, coefficient of variation = 12%

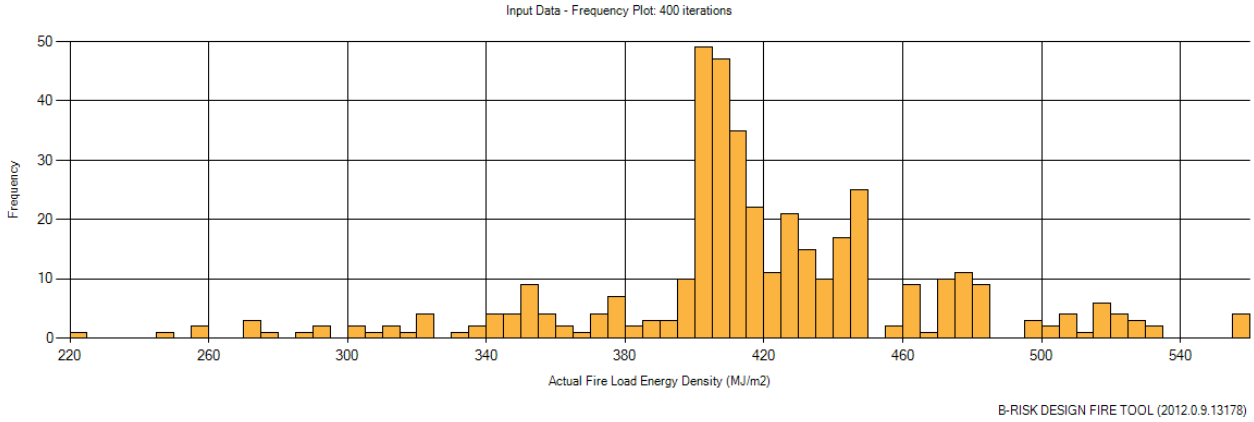


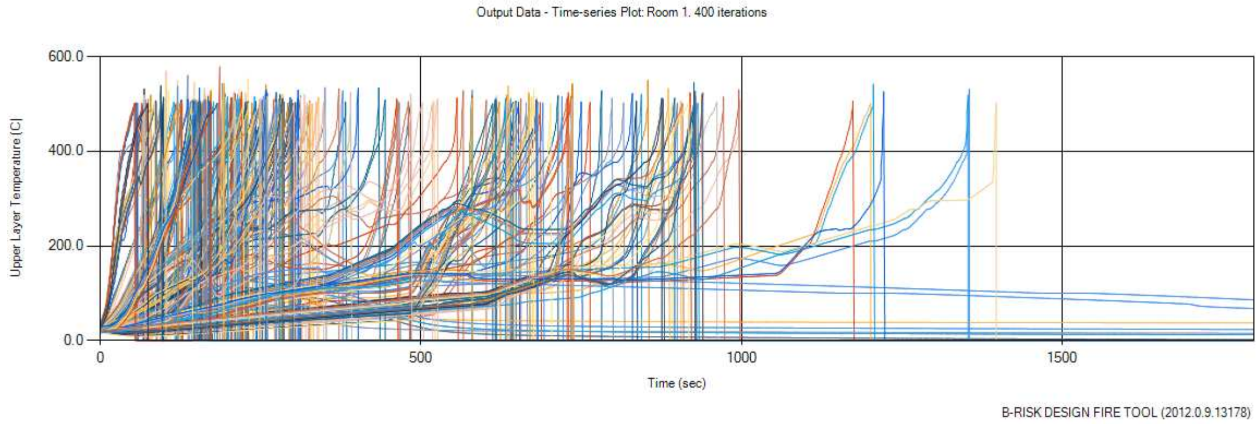


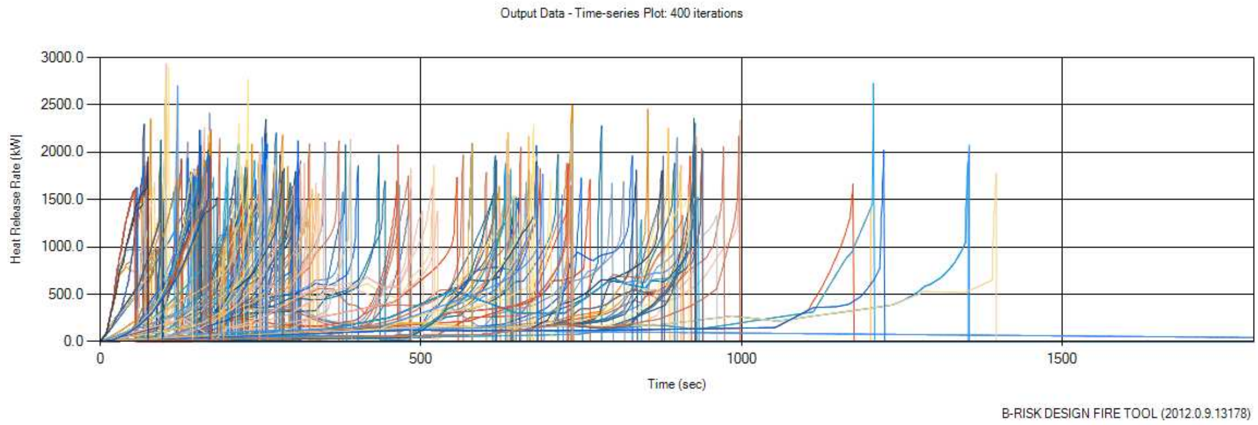


Section 6.3, Case B, target FLED = 400 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 419 MJ/m^2, standard deviation = 51 MJ/m^2, coefficient of variation = 12%

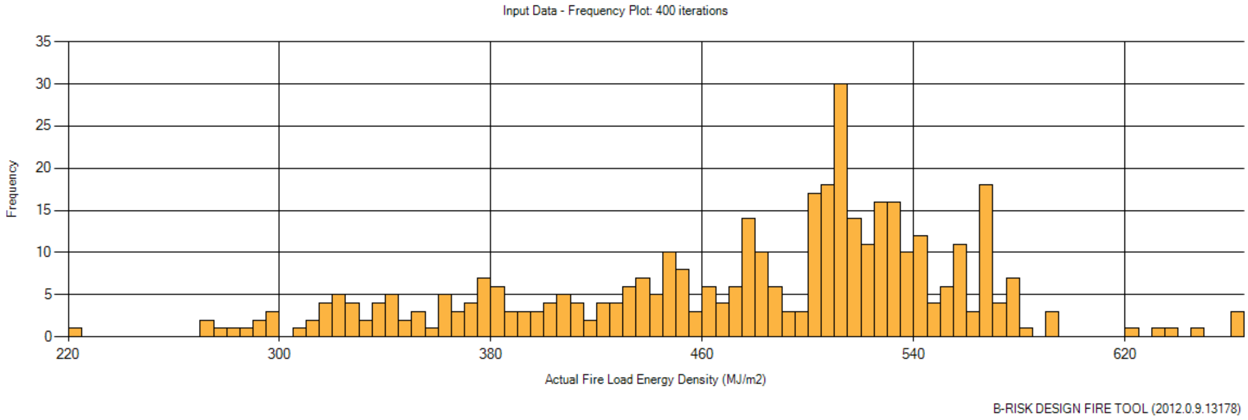


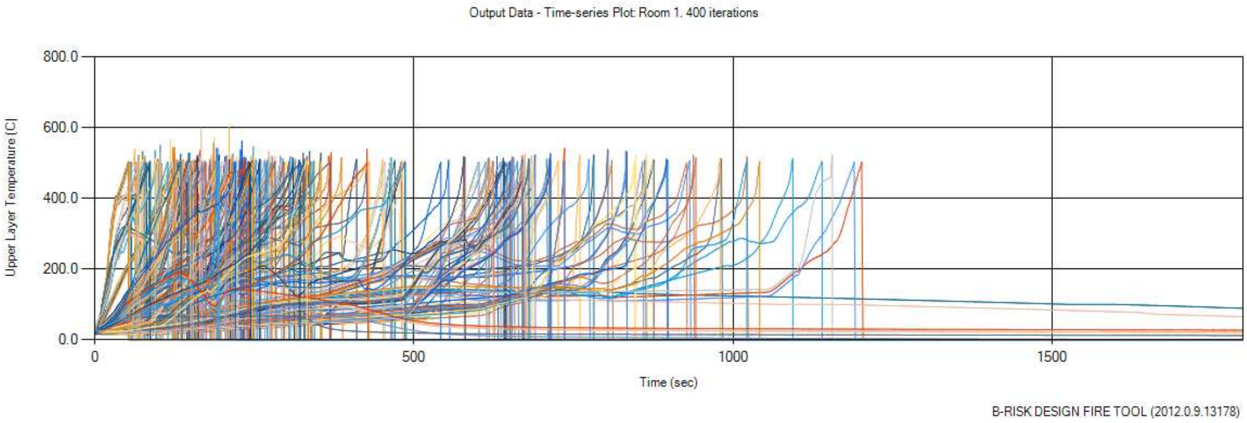


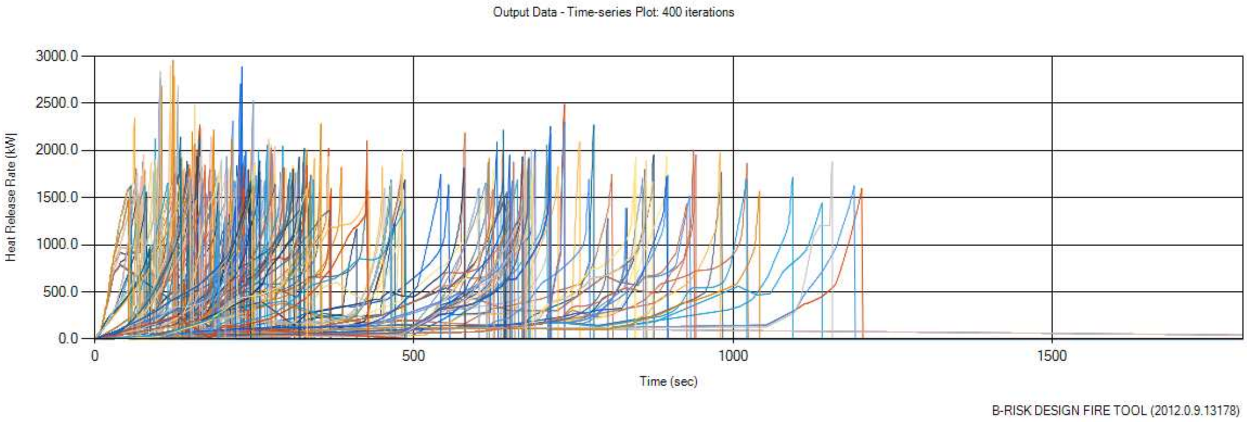


Section 6.3, Case B, target FLED = 500 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 476 MJ/m^2, standard deviation = 80 MJ/m^2, coefficient of variation = 17%

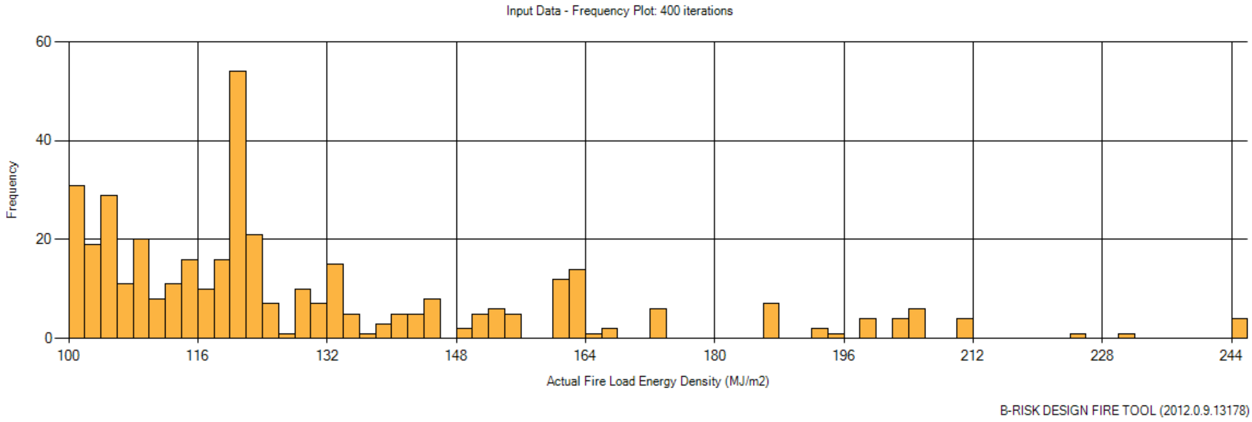


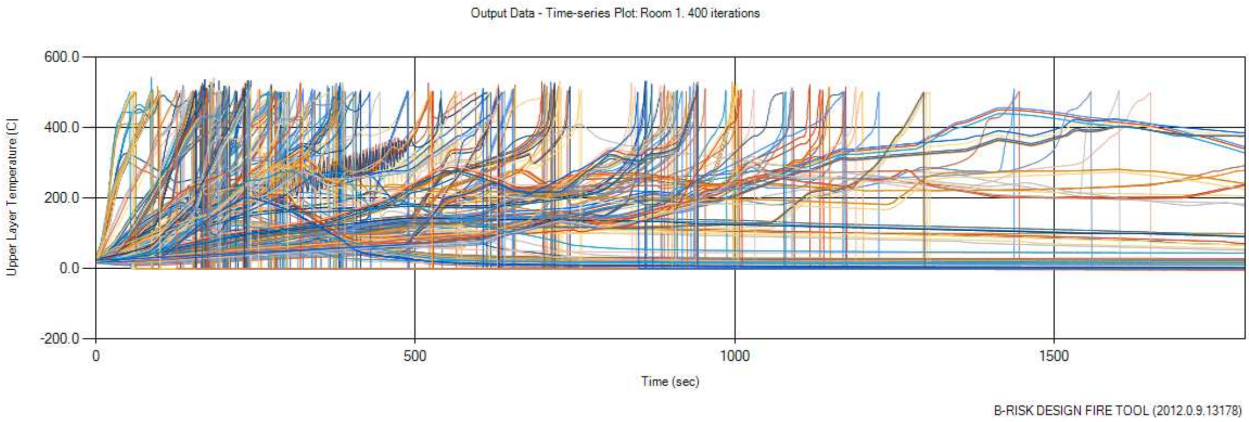


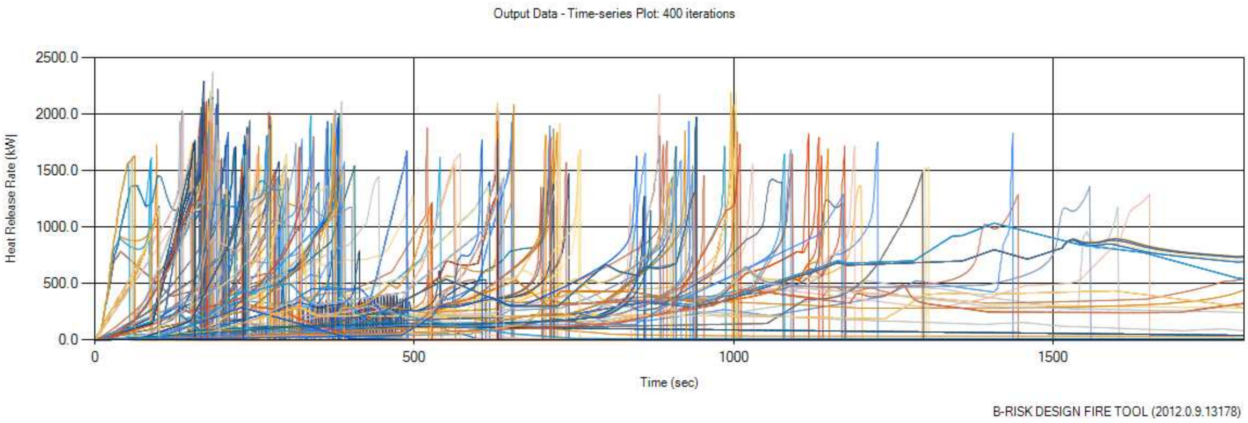


Section 6.3, Case C, target FLED = 100 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 131 MJ/m^2, standard deviation = 30 MJ/m^2, coefficient of variation = 23%

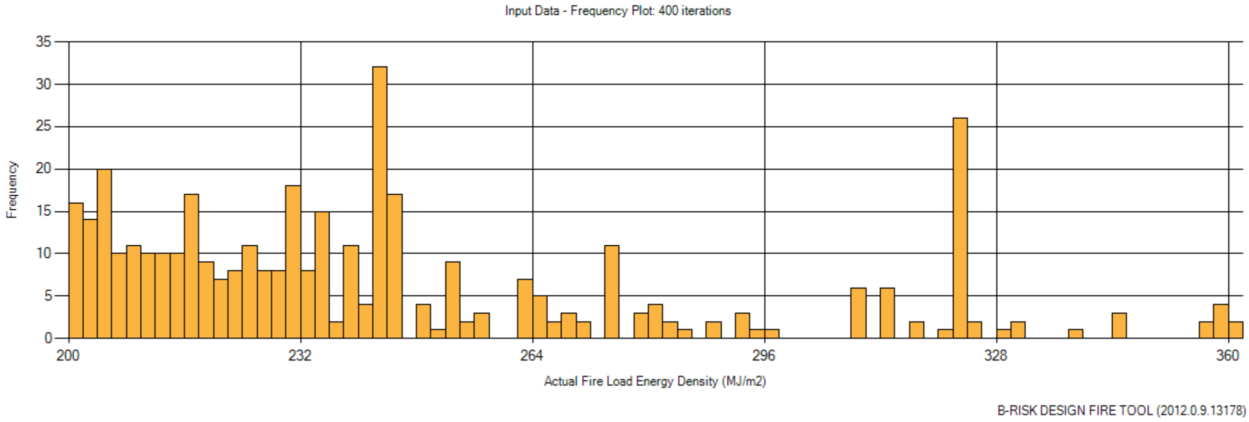


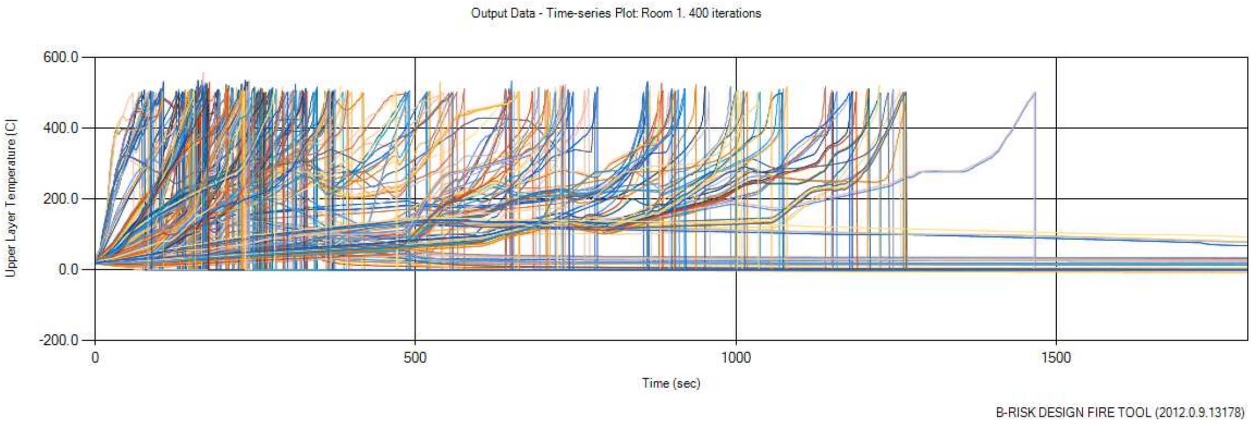


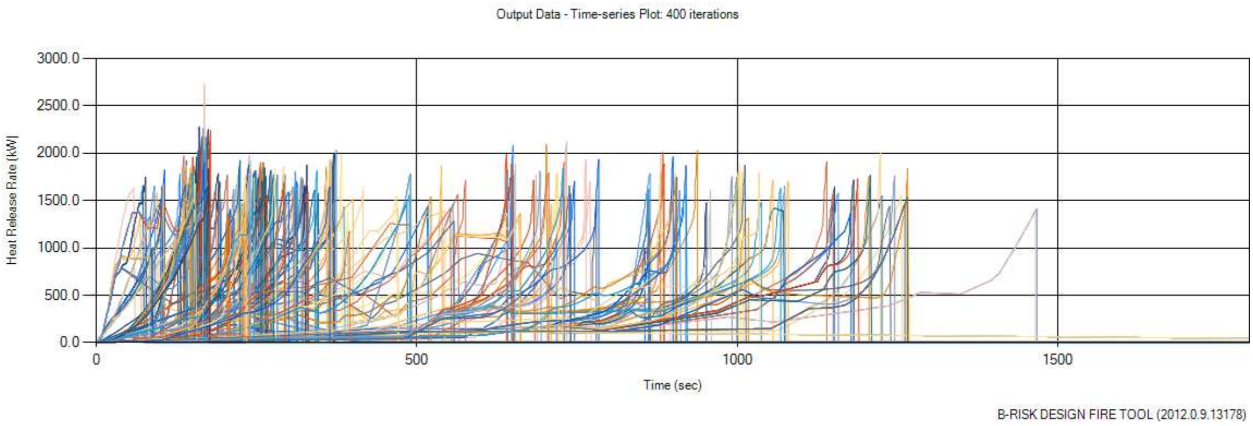


Section 6.3, Case C, target FLED = 200 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 246 MJ/m^2, standard deviation = 40 MJ/m^2, coefficient of variation = 16%

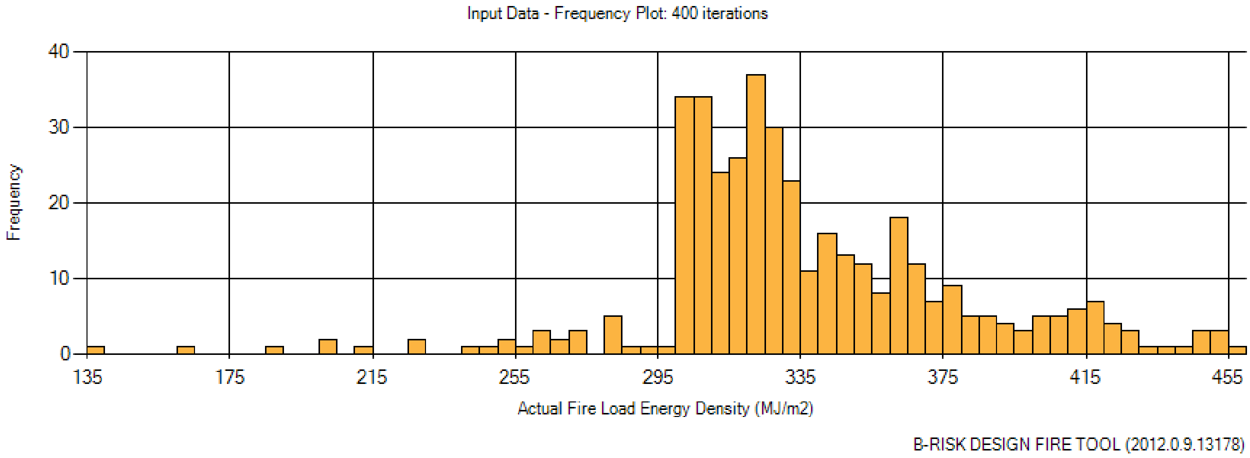


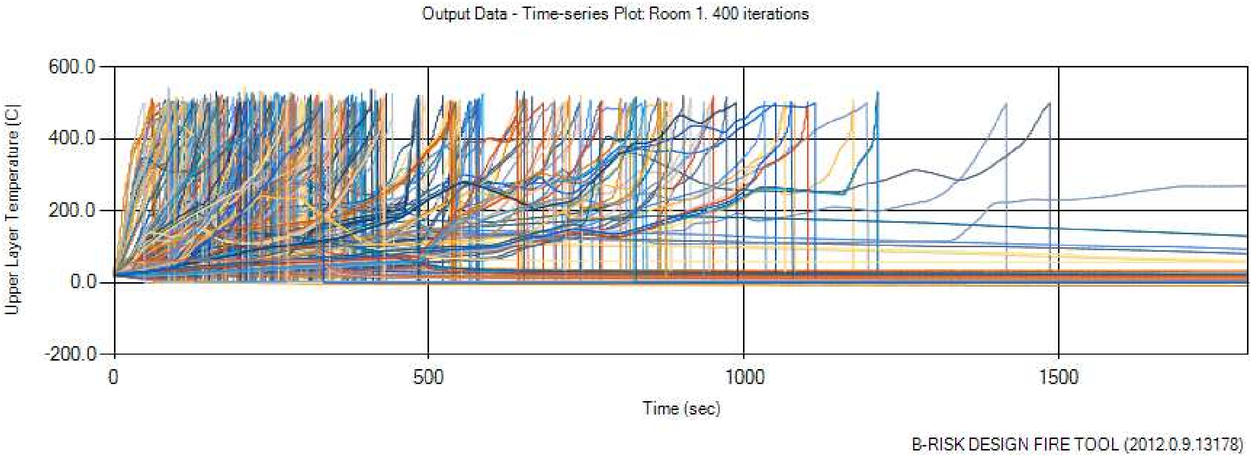


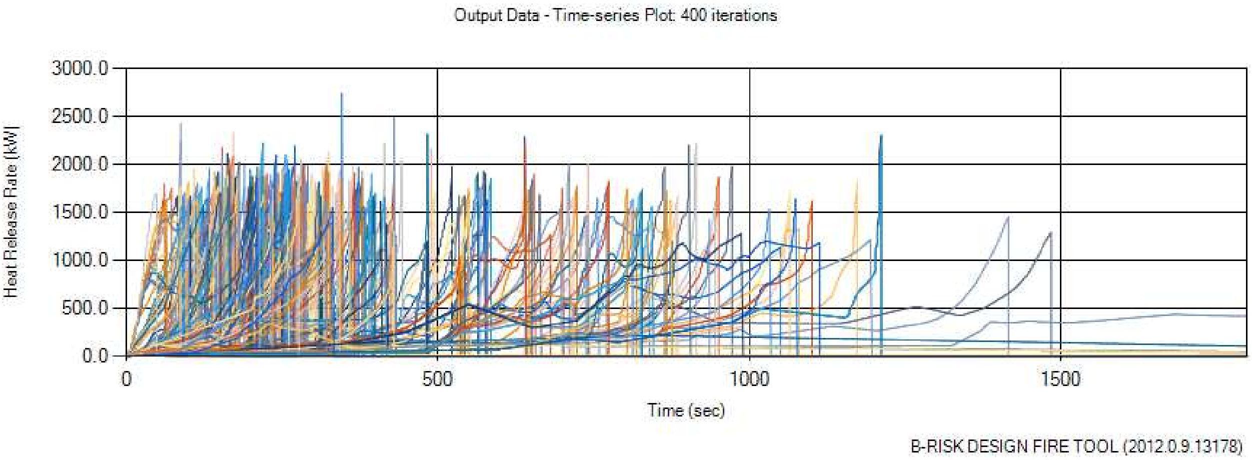


Section 6.3, Case C, target FLED = 300 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 336 MJ/m^2, standard deviation = 44 MJ/m^2, coefficient of variation = 13%

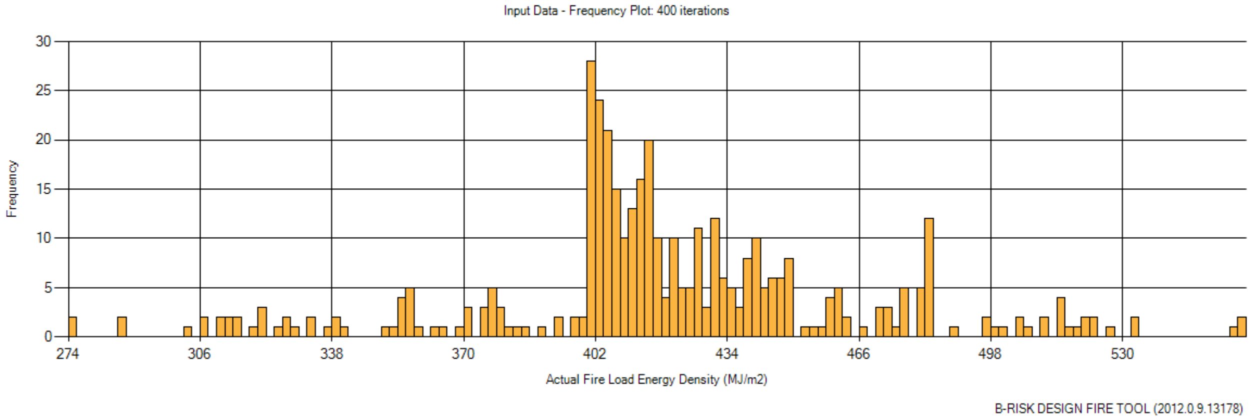


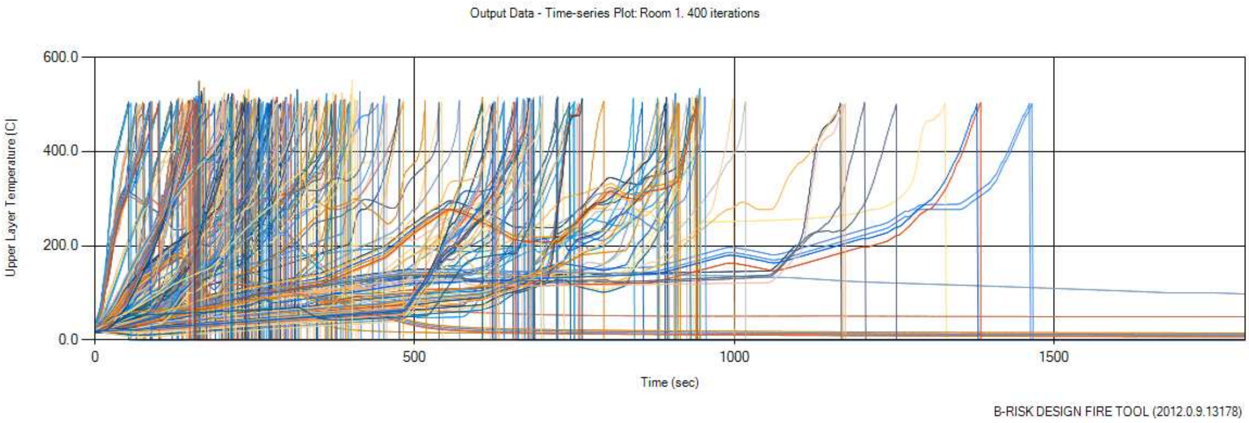


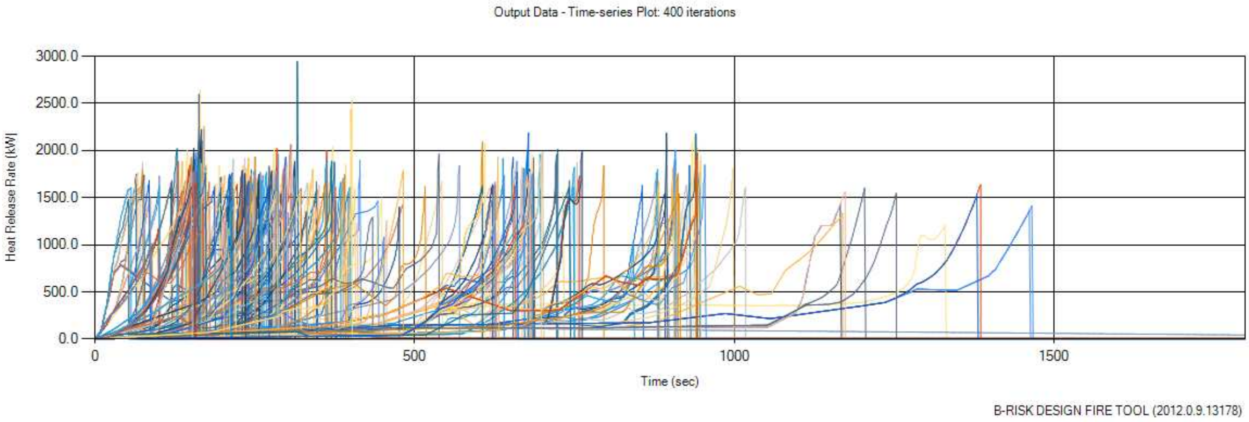


Section 6.3, Case C, target FLED = 400 MJ/m^2 (graphs generated by B-RISK)

Actual FLED: mean = 420 MJ/m^2, standard deviation = 46 MJ/m^2, coefficient of variation = 11%

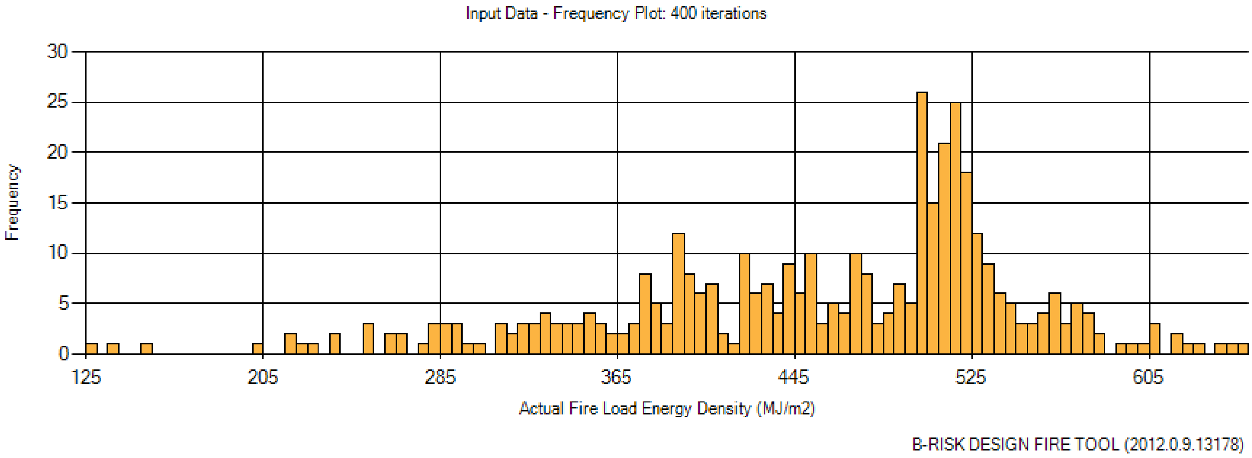


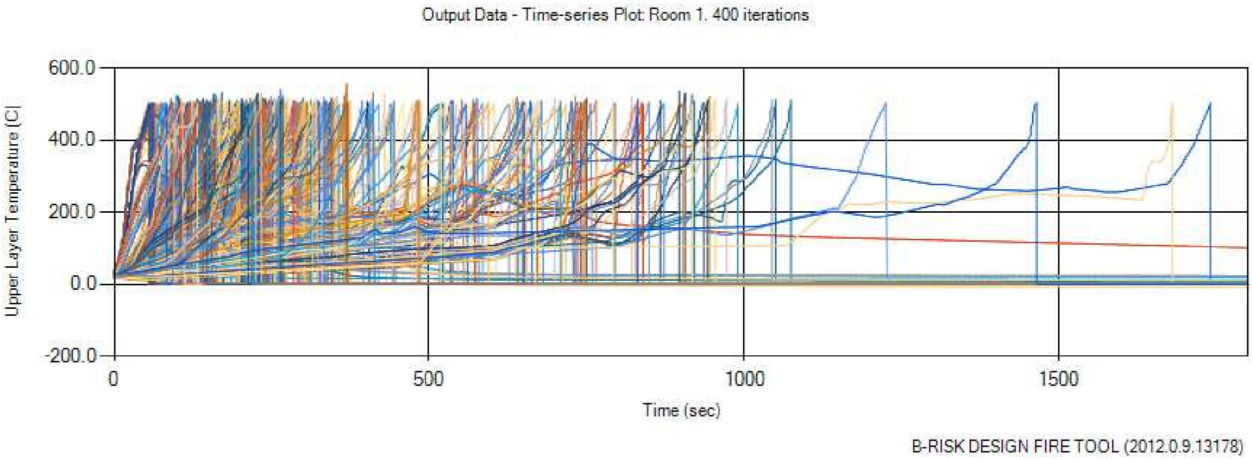


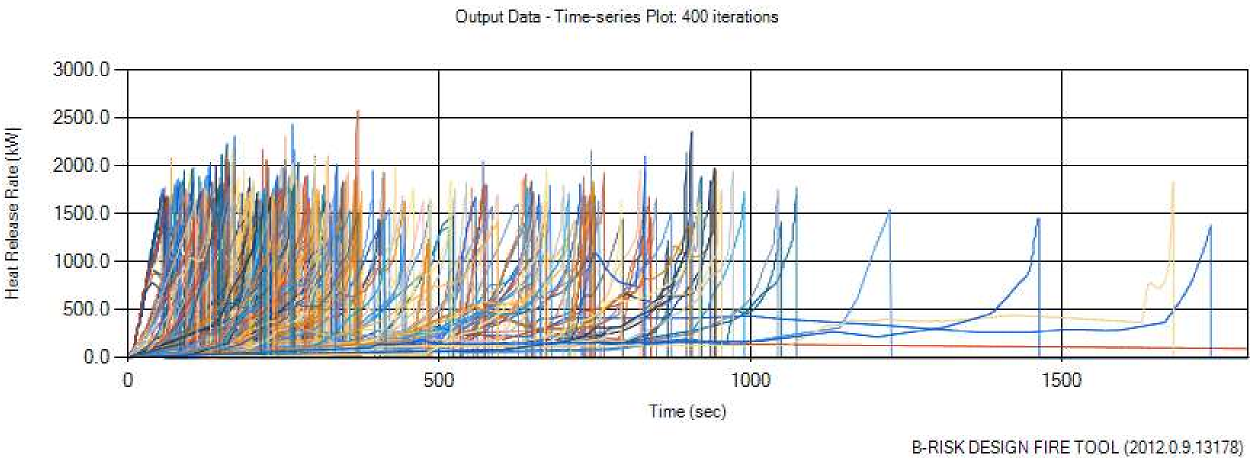


Section 6.3, Case C, target FLED = 500 MJ/m^2 (graphs generated by B-RISK)

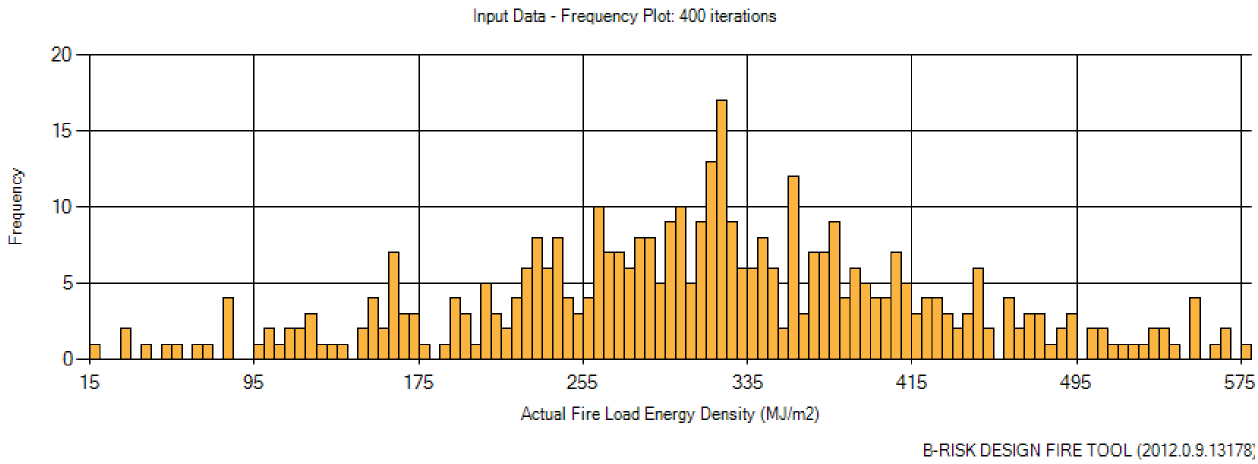
Actual FLED: mean = 458 MJ/m^2, standard deviation = 91 MJ/m^2, coefficient of variation = 20%

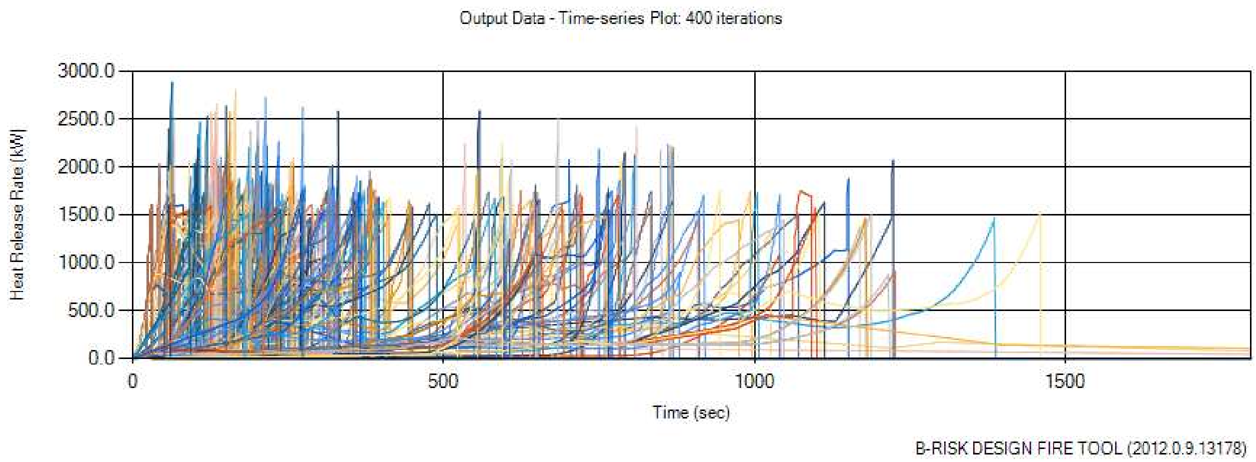




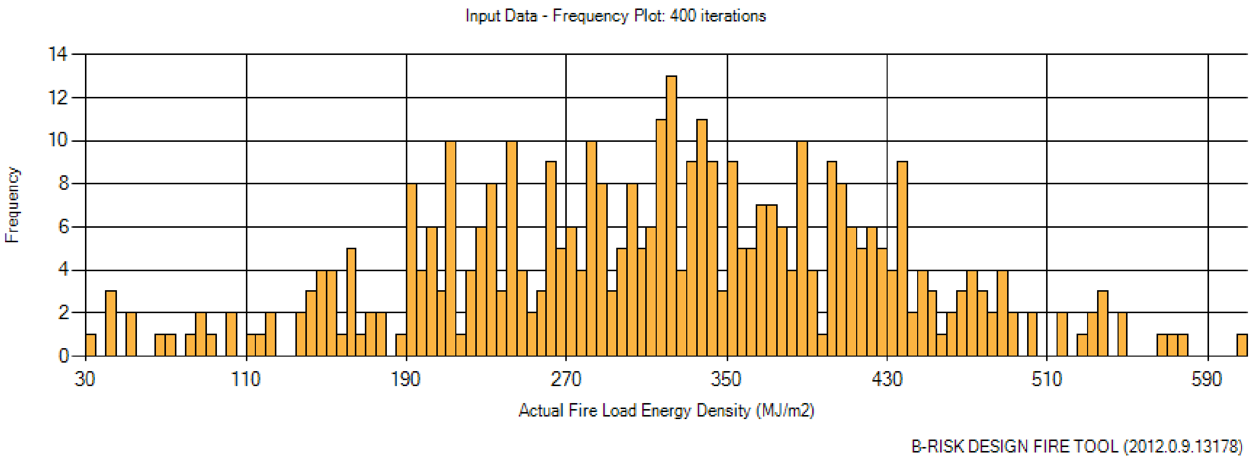


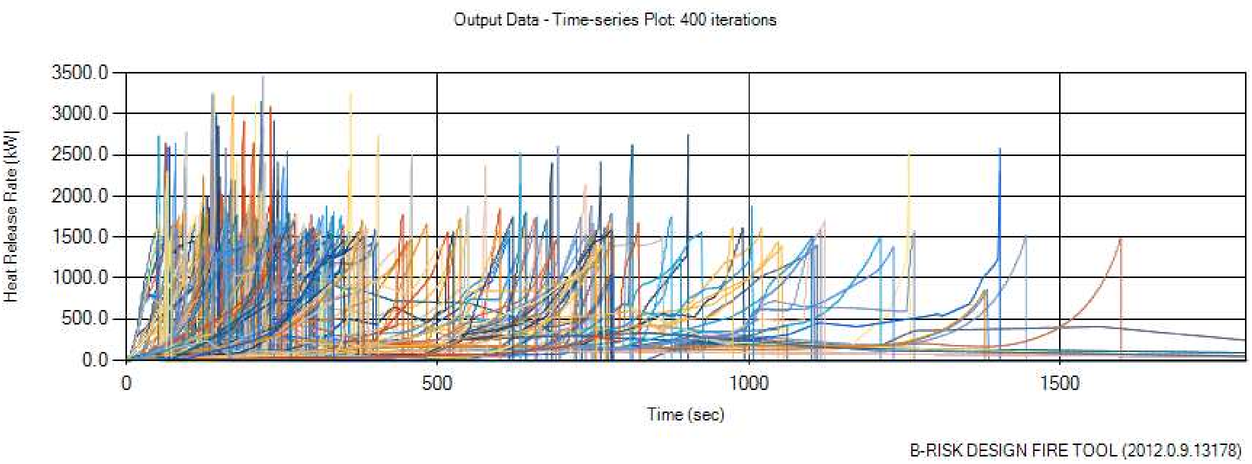
Section 6.4, plywood FR (graphs generated by B-RISK)



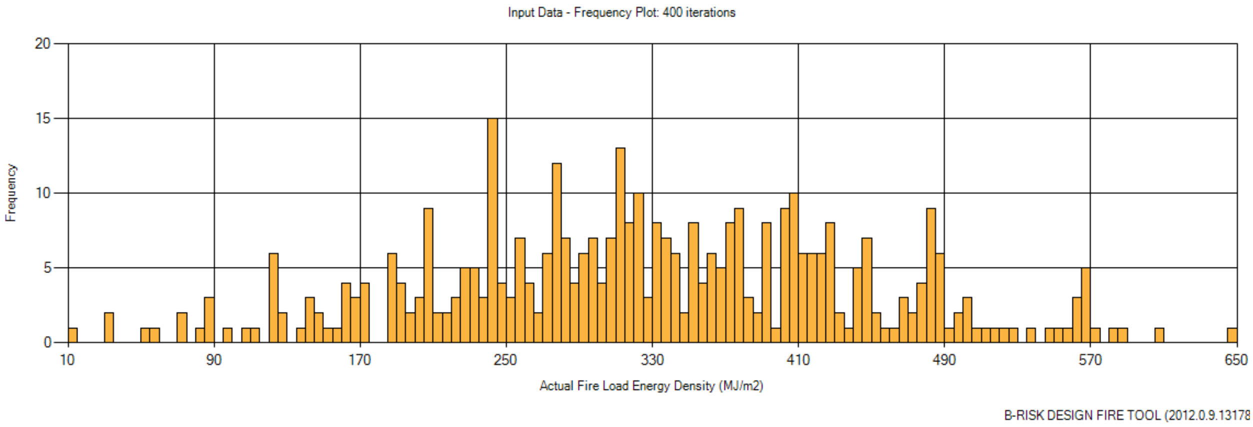


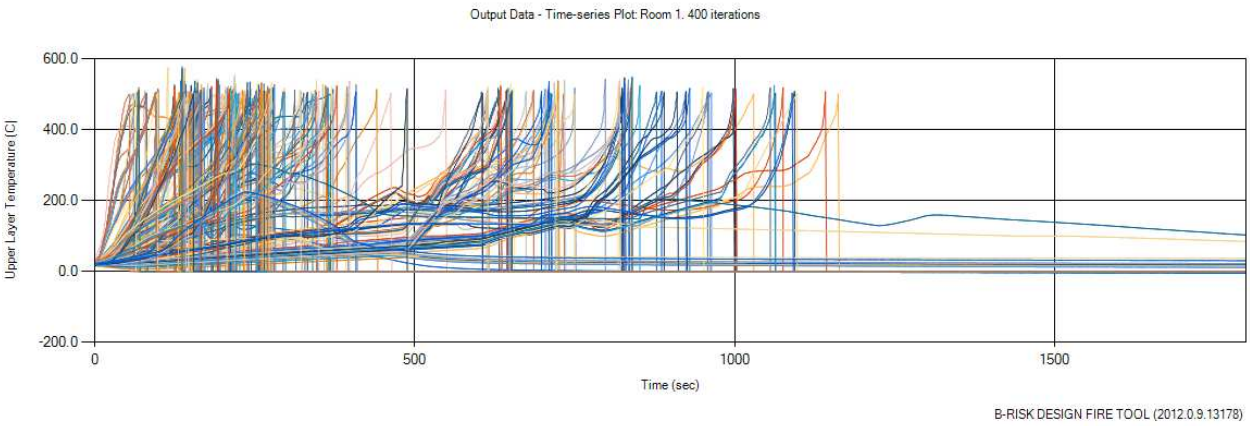
Section 6.4, MDF (graphs generated by B-RISK)

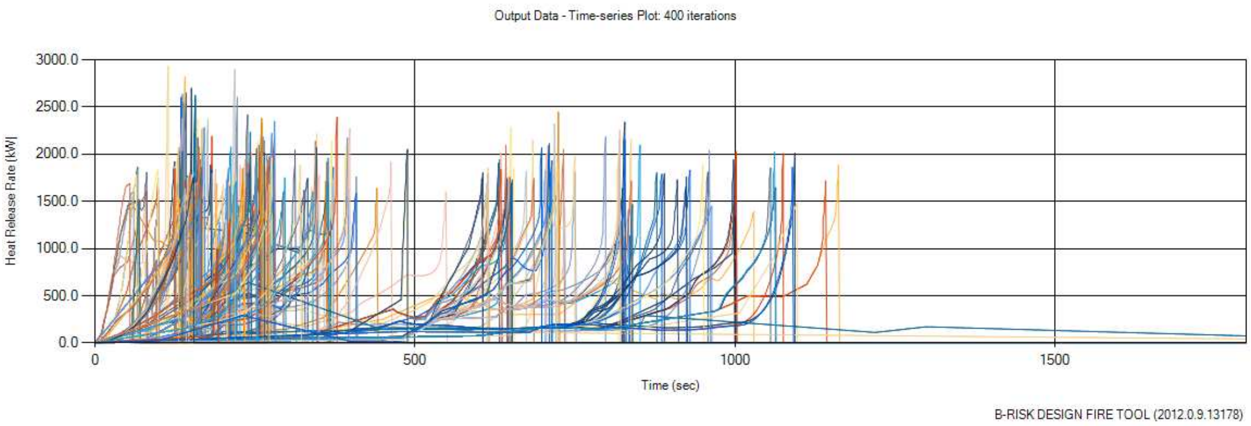




Section 6.5, probability 0.2 (Graphs generated by B-RISK)







Section 6.5, probability 0.8 (Graphs generated by B-RISK. Simulations were performed in two instalments with 58 and 342 iterations. Graphs are shown for the 342 iterations' simulation only.)